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FOREWORD

This report is intended to be a single-source document describing the U.S. Army Research Office (ARO) research programs for FY09. It includes:

- A brief review of the strategy employed to guide ARO research investments and noteworthy issues affecting the implementation of that strategy;
- statistical information on 6.1 funding and program proposal activity; and
- research trends and accomplishments of the individual ARO scientific divisions.

The vision of the Director, Army Research Office (ARO) is to execute the Army extramural basic research program in the physical sciences (physics, chemistry, life sciences), the engineering sciences (mechanical, electrical, materials, environmental), and mathematics and information sciences (mathematics, computing and informational sciences). The goal of the research is to drive science and develop solutions for the US Army through university, industry and government partnerships by exploring high-risk, high pay-off opportunities. The scope of ARO research is broad and decidedly long range with system applications solutions 10 to 15 or more years away. However, there have been many research programs that have had near-term spin-offs to system application in much shorter times. This approach is designed to maintain the Army's overwhelming capability in the expanding range of present and future operations.

Focusing scientific talent on the needs of the Army is ARO's mission of conducting discovery research targeted at developing advances that will insure continuing technological superiority. Further, ARO guides the transition of those advances to the appropriate applied research and advanced development organizations. The ARO is also actively engaged in speeding the transition of discovery into systems. This is achieved primarily through active involvement in the development of topics and the management of projects in the Small Business Innovation Research and Small Business Technology Transfer programs. Recognizing that it is critical for the future of the nation to develop a highly educated workforce skilled in DoD and Army relevant science and engineering, the ARO also has an extensive program in outreach to pre-graduate education, and in fostering the development of Historically Black Colleges and Universities and Minority Institutions. In addition to these efforts the ARO Director emphasizes a two-pronged investment strategy: requirements pull and technology push. Following classic Joint Capabilities Integrated Development System processes, ARO responds to a wide variety of published requirements including the Army Science and Technology Master Plan and Training and Doctrine Command Warfighter Objectives (requirements pull). However, recognizing that not all success is borne of *a priori* planning, ARO also invests heavily in discovery research targeted at extraordinarily novel and innovative science that might not specifically foretell of a military application, but promises tremendous value when mature.

FOREWORD

While the Army Material Command's Research, Development and Engineering Command (RDECOM) is the primary user of the results of the ARO research program, ARO also supports research on behalf of the Army Corps of Engineers, the Army Medical Research and Materiel Command, and other Army Commands and Department of Defense (DoD) agencies. Coordination and monitoring of the ARO extramural program by the Army Research Laboratory Directorates; Research, Development and Engineering Centers; and other Army laboratories ensure a highly productive and cost-effective Army research effort. University Affiliated Research Centers (UARC) and Multidisciplinary University Research Initiative (MURI) centers benefit from the expertise and guidance provided by the Army Research Laboratory Directorates, Research, Development and Engineering Centers, and other DoD, academic, and industry representatives who serve on Executive Steering Boards and Technical Assessment Councils for each university center. The Office of the Secretary of Defense (OSD) research programs managed by ARO fall under the executive oversight of the Defense Basic Research Advisory Group. Other members on of this group include the Director of Research, Office of the Deputy Under Secretary of Defense (Science and Technology) and representatives from the Office of Naval Research (ONR), the Air Force Office of Scientific Research (AFOSR) and the Defense Advanced Research Projects Agency (DARPA).

The research programs described below are direct-funded from Army Program Elements "Defense Research Sciences," "University/Industrial Research Centers," and "University Research Initiatives" (URI). Research supported with customer funds (e.g., the Defense Advanced Research Projects Agency) is included in the description of closely aligned ARO programs as appropriate.

ARO INVESTMENT STRATEGY

The U.S. Army Research Office (ARO) strategic vision is to conduct an aggressive basic science research program on behalf of the Army that insures cutting-edge scientific discoveries and optimally develop the general scientific knowledge resulting in improved weapons systems that establish land force dominance. Formulation of programs are accomplished through an on-going and active collaboration with the Army Research Laboratory Directorates; the Research, Development and Engineering Command's Research, Development and Engineering Centers; the Army Medical Research and Materiel Command; the Army Corps of Engineers; the Army Research Institute for the Behavioral and Social Sciences; the Army Training and Doctrine Command; and other federal research organizations. These developed programs utilize the Defense Science and Technology Reliance process active within the Basic Research Panel to coordinate and plan current and future research thrusts.

Strategies to meet the vision are:

- Execution of an integrated, balanced extramural basic research program.
- Accelerate research results transition to applications in all stages of the research and development cycle.
- Stimulate the discovery and application of novel scientific phenomena leading to leap-ahead technologies for the Army.
- Strengthen academic, industrial, and nonprofit laboratories research infrastructures, which serve the Army.
- Focus on those research topics that support technologies vital to the Army's future force, combating terrorism and new emerging threats.
- Direct efforts in research areas relating to new opportunities for Army applications which underscore the role of affordability and dual-use, especially as they provide new Force Operating Capabilities and responses to anticipated emerging threats.
- Leverage the science and technology of other defense and Government laboratories, academia and industry, and appropriate organizations of our allies.
- Foster scientists and engineers training in the disciplines critical to Army needs.
- Actively seek creative approaches to enhance education and research programs at Historically Black Colleges and Universities and at Minority Institutions.

To implement this strategy, the ARO extramural research program uses single investigator efforts, Multidisciplinary University Research Initiatives (MURIs), University Affiliated Research Centers, and specially tailored outreach programs. Each research approach has its own set of objectives and advantages. This strategy is

employed by the ARO to the maximum extent possible in planning the University Research Initiative programs sponsored by the Office of Deputy Undersecretary of Defense (Science and Technology).

GENERAL INFORMATION

This section of the report addresses issues affecting the implementation of the research programs managed by the U.S. Army Research Office (ARO) in FY09.

Project BH57 represents the core research budget provided to ARO by the Army. The actual release of funds to Project BH57 this year was $63.4M. This represented an $8.8M increase over the FY08 amount thus increasing monies for single investigator research.

Through funds provided by ARO Project H05, ARO continued to fund the Institute for Collaborative Biotechnologies (ICB) at the University of California – Santa Barbara. This University Affiliate Research Center focuses on sensors, electronics and information processing biotechnology and the underpinning biotechnology fundamentals. In FY09, the ICB received $10.7M in 6.1. The universities selected as ICB partners are: Massachusetts Institute of Technology and California Institute of Technology.

In FY04, the Office of the Secretary of Defense (OSD) funding for the University Research Initiative (URI) program was devolved to the services, including the Army. The URI devolvement was continued in FY09, and the funds were continued to be used to support the same types of programs as in the past: for example, new research topics under the Multidisciplinary University Research Initiative (MURI) Program in FY09 continued to support DoD Strategic Research Areas or other approved OSD research topics. The total FY09 URI funding was $74.6M.

Just as in the previous year, the largest single source of research funding to ARO in FY09 was the Defense Advanced Research Projects Agency (DARPA). DARPA provided $100.9M of FY08 and FY09 funds for such key research areas as compact, lightweight power sources, smart structures, optoelectronics, nanostructure fabrication, multi-agent systems, and materials for photonic systems. The ARO Physics Division continued to manage a multi-million dollar program in quantum computing with funds from both DARPA and the National Security Agency.

Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) Programs

Congress established the Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) Programs to provide small businesses and research institutions with opportunities to participate in government-sponsored research and development. SBIR was established in 1982 and has been reauthorized through 2008 and extended through 2009, while STTR was established in 1994 and is currently authorized through 2009.

The Army-wide SBIR program is managed at RDECOM. The Army-wide STTR program is managed at ARO.

PROGRAM IMPLEMENTATION

The goals of the SBIR and STTR programs are to: (1) stimulate technological innovation; (2) use small business to meet Federal R/R&D needs; (3) foster and encourage participation by socially and economically disadvantaged small business concerns (SBCs; and (4) increase private sector commercialization of innovations derived from Federal R/R&D, thereby increasing competition, productivity and economic growth. Congressional mandate requires that all federal agencies with an annual extramural R&D budget exceeding $100 million participate in the SBIR program. The Army SBIR budget is computed as 2.5 percent of the agency's extramural R&D budget and is $265 million for FY09. ARO obligated $12Munder its portion of the Army SBIR program. During FY09, 17 proposals (nine Phase I and eight Phase II) were selected for award by ARO of the 454 selected throughout the Army. The STTR budget is computed as .3 percent of the agency's extramural R&D budget and was $31.9M in FY09.

The U.S. Small Business Administration (SBA) is responsible for the government-wide SBIR and STTR Programs and develops policy and guidance and reports SBIR/STTR data and statistics to the Administration and Congress. Each federal agency manages its SBIR/STTR Program independently in accordance with SBA policy. The Army participates under the Department of Defense (DoD) SBIR/STTR Program structure. The SBIR Program is open to any small business, defined as a business having no more than 500 employees (including all affiliates), which is operated in the USA and at least 51% owned by a U.S. citizen or permanent resident alien. The small business may subcontract a portion of its work, so long as the small business "prime" performs at least two-thirds of the Phase I work and half of the Phase II work. For the purposes of determining compliance, percent of work is usually measured by both direct and indirect costs; however, the actual method of measurement will be verified during contract negotiations.

The STTR Program is open to any team consisting of a small business (as defined above) and a research institute. Central to the program is expansion of the public/private sector partnership to include the joint venture opportunities for small business and the nation's premier nonprofit research institutions. STTR's most important role is to foster the innovation necessary to meet the nation's scientific and technological challenges in the 21st century. The research institute may be any U.S.-based nonprofit research institution, federally funded research and development center (FFRDC), or university or college. The small business must perform at least 40% of the Phase I and Phase II work. The research institute must perform at least 30% of the Phase I and Phase II work. Up to 30% of the work may be subcontracted to others.

For the DoD SBIR Program Phase I and II efforts, the primary employment of the principal investigator must be with the small business firm at the time of the award and during the conduct of the proposed effort. Primary employment means that more than one-half of the principal investigator's time is spent with the small business. For the STTR Program Phase I and II efforts, the principal investigator must be primarily employed with the small business firm or the research institution.

For both programs, the Phase I and Phase II work must be performed in the United States, to include the Commonwealth of Puerto Rico, the Commonwealth of the Northern Mariana Islands, the Trust Territory of the Pacific Islands, and the District of Columbia.

Each year, along with other DoD components, the Army generates and publishes a set of high-priority topics in SBIR and STTR solicitations and invites small businesses to submit proposals dealing with these topics. The topics reflect the user community's interests and Force Operating Capabilities (FOCs) as expressed in TRADOC PAMPHLET 525-66. All Army topics will also reflect Warfighter Outcome requirements as identified by TRADOC, and at the same time be aligned with Army Technology Objectives (ATOs), and Advanced Technology Demonstrations (ATDs). Army stakeholders from TRADOC, Logistics Transformation Agency, ManTech, PMs/PEOs and the RDECOM Technology Teams (Technology Integration Focus Teams, Technology Knowledge Centers, and Operations) have an opportunity to review and endorse topics. Fifty percent of the Army's SBIR topics must be endorsed or co-authored by an Acquisition Program (PM or PEO). All Army STTR topics must be correlated with DoD Key Technology Areas (KTAs) and normally with ATOs and FOCs as well. PM/PEO interactions are encouraged but not required.

Both programs use a three-phase process, reflecting the high degree of technical risk involved in developing and commercializing cutting edge technologies.

Phase I is a feasibility study that determines the scientific, technical, and commercial merit and feasibility of a selected concept. Phase I projects are competitively selected from proposals submitted against annual solicitations. Each solicitation contains topics seeking specific solutions to stated government needs. The Army publishes its SBIR topics in all three DoD SBIR solicitations each year. The Army publishes its STTR topics in one annual DoD STTR solicitation, which generally opens in February of each year.

The Army SBIR and STTR Phase I selection process is highly competitive, with typically one out of ten submitted Phase I proposals receiving awards.

Phase II represents a major research and development effort, culminating in a well-defined deliverable prototype (i.e., a technology, product, or service). The Phase II selection process is also highly competitive. Successful Phase I contractors are invited to submit Phase II proposals as there are no separate Phase II solicitations. Typically 50% of Phase II proposals are selected for award.

In Phase III, the small business or research institute is expected to obtain funding from the private sector and/or non-SBIR/STTR government sources to develop the prototype into a viable product or service for sale in the military or private sector markets.

Since 2008, RDECs have been invited to participate in the Army STTR program. Also, the Army STTR web-based system of proposal evaluation has been extended to OSD STTR items with Army topic chiefs. There are several basic differences between the

SBIR and STTR Programs within the above 3-phase structure. The following table compares the two programs.

PHASES	SBIR	STTR
Phase I	• 6 months, $70,000 max • 4-month option (at Government's discretion if Phase II proposal is selected), $50k max, to fund interim Phase II efforts.	• Six months, $100,000 max • No options
Phase II	• 2 years, $730,000 max	• 2 years, $750,000
Phase III	• No time limit • No SBIR funds	• No time limit • No STTR funds

Figure 1 - Phases of SBIR/STTR Programs

For more information about Army–specific SBIR/STTR, visit http://www.armysbir.com and the DoD SBIR/STTR Program Office maintains a web site with more information about the SBIR/STTR programs at http://www.acq.osd.mil/sadbu/sbir.

Training and Doctrine Command Battle Labs - The Army Training and Doctrine Command (TRADOC) established the Battle Labs to demonstrate and assess new doctrines, strategies, warfighting methods, and technologies within the context of the future Army. The Battle Labs conduct live, virtual, and constructive simulations to determine the warfighting merits of new ideas, concepts, and technologies – including those of industry. The Battle Labs are organized around the major battlefield dynamics: Air Maneuver, Air and Missile Defense, Battle Command, Combat Service Support, Depth and Simultaneous Attack, Dismounted Battlespace, Maneuver Support, Mounted Maneuver Battlespace, and Space and Missile Defense. TRADOC's Force Operational Capabilities are correlated with candidate SBIR and STTR topics.

Short Term Innovative Research Program - The objectives of the Short Term Innovative Research (STIR) Program are to find innovative ideas in basic research. Proposed research may be for the continuation or the natural outgrowth of experimental or theoretical exploration. Research proposals are sought from educational institutions, nonprofit organizations, or private industry.

University Research Initiative (URI) and other Office of the Secretary of Defense (OSD) Programs - OSD 6.1 direct funding to ARO through the Office of the Director for Defense Research & Engineering (ODDRE) generally exceeds the level of Army 6.1 direct funds awarded to universities by ARO. However, more than the magnitude of dollars, the scope and variability of this activity in terms of objectives (research, instrumentation, education, etc) and targeted groups (minority institutions, selected states, etc) add a complexity to planning and execution far in excess of ARO's Army-funded programs.

Current OSD-budgeted initiatives include:

- Multidisciplinary University Research Initiative (MURI) Program;
- Defense Experimental Program to Stimulate Competitive Research (DEPSCoR);
- Defense University Research Instrumentation Program (DURIP);
- National Defense Science and Engineering Graduate (NDSEG) Fellowships;
- Infrastructure Support Program (ISP) for Historically Black Colleges & Universities and Minority Institutions (HBCU/MI); and
- Presidential Early Career Awards for Scientists and Engineers (PECASE).

Each of these ODDRE-mandated activities has a different focus and/or different target audience. The ARO has been designated by the Director of Research/ODDRE as the lead agency for the implementation of two of the DoD programs on behalf of the three Services plus the Agencies of the Department of Defense. These are the DEPSCoR and ISP-for-HBCU/MI activities. A brief description of each of the multi-year programs follows.

Multidisciplinary Research Initiative (MURI) Program - The Multidisciplinary University Research Initiative (MURI) Program of the University Research Initiative (URI), supports university teams whose research efforts intersect more than one traditional science and engineering discipline. The DoD believes that multidisciplinary team efforts can accelerate research progress through synergy and cross-fertilization of ideas. Such team efforts can help to hasten the transfer of basic research findings to practical applications. The essential features of the MURI program are the same as those of the original URI but the scope of each award is generally larger and there are subsequently fewer awards with these annual solicitations. The awards are 5 year grants to support research, graduate students and laboratory instrumentation development. MURI grants typically range from $1M to $1.5M per year (three year increments plus two year options). The two year funding option is subject to satisfactory progress in the research and the availability of funding appropriations.

Given the large size of these awards, it is expected more research results are achievable by collaboration among multiple investigators. Management oversight of the MURI program comes from the Research Office of DDR&E to the OXRs, where the MURI projects are managed by OXR program managers. Program managers have a lot of flexibility and discretion in how they monitor and manage the individual projects, while DDR&E defends the program to higher level in OSD and has responsibility for overall program direction and oversight.

The Department of the Army provides funding for the Multidisciplinary Research Program, one element of the URI. The University Research Initiative is a DoD initiative

with the goal of enhancing the capabilities of universities to perform basic research in science and engineering fields critical to national defense. Selection of the Army research topics and the eventual awards are closely reviewed and approved by ODDR&E under a formal acquisition process. The DoD expects MURI programs to focus on basic research in science and engineering that will eventually lead to applications for defense purposes primarily, but also for commercial purposes. Therefore, cooperative linkages with research and development institutions outside the MURI team that apply research findings to practical use are important. Such institutions include U.S. industry, federal laboratories, and DoD organizations that perform research and development for defense applications.

Topics that resulted in 12 newly funded Army centers for FY09 were:

1. Disruptive Fibers for Flexible Armor, Dr. Douglas Kiserow, Chemistry and Dr. David Stepp, Materials Science
2. Network-based Hard/Soft Information Fusion, Dr. John Lavery, Mathematics
3. Tailored Stress-Wave Mitigation, Dr. David Stepp, Materials Science and Dr. Bruce LaMattina, Mechanical Sciences
4. Integrated Quantum Circuits, Dr. T.R. Govindan, Physics
5. Adaptive Structural Materials, Dr. Douglas Kiserow, Chemistry
6. Transformational Optics, Dr. Richard Hammond, Physics
7. Emergent Phenomena at Complex Oxide Interfaces, Dr. Marc Ulrich, Physics
8. Application of Systems Biology to Regenerative Medicine, Dr**.** Micheline Strand, Biology
9. Mechanisms of Bacterial Spore Germination, Dr. Wallace Buchholz, Biology and Dr. Harry Chang, Mathematics
10. Opportunistic Sensing, Dr. Liyi Dai, Computer & Information
11. Cyber Situation Awareness, Dr. Cliff Wang, Computer & Information

Topics that the Army has entered into the FY2010 MURI Program announcement are:

1. Neuronal Behavior in Primary Blast, Dr. Elmar Schmeisser, Life Sciences and Dr. Bruce LaMattina, Mechanical Sciences
2. Identifying and Extracting the Mathematical Signatures of Prokaryotic Activity in DNA; Developing a Theoretical Foundation for Predicting DNA Stability, Dr. Mimi Strand, Life Sciences; Dr. Janet Spoonamore, Network Sciences and Dr. Wallace Buchholz, Life Sciences

3. Tomography of Social Networks of Asymmetric Adversaries, Dr. John Lavery, Mathematics

4. Adaptive Perception and Agile Autonomy in Severe Environments, Dr. Randy Zachery, Network Sciences

5. Structured Modeling for Low-Density Languages, Dr. Joseph Myers, Computing Sciences

6. Directed Self-Assembly of Reconfigurable Materials, Dr. John Prater, Materials Science & Dr. Douglas Kiserow, Chemistry

7. "Atomtronics": A generalized electronics, Dr. Marc Ulrich, Physics

8. Bio-Electronic Templates for Interfacing to the Nanoscale, Dr. Dwight Woolard, Electronics & Dr. Richard Hammond, Physics

9. Ion Transport In Complex Heterogeneous Organic Materials, Dr. Robert Mantz, Chemistry & Dr. David Stepp, Materials Science

10. Defect Reduction in Superlattice Materials, Dr. William Clark, Electronics; Dr. John Prater, Materials Science & Dr. Marc Ulrich, Physics

Defense Experimental Program to Stimulate Competitive Research (DEPSCoR) - The DEPSCoR program improves the capabilities of universities in selected states by supporting research and the education of scientist and engineers in areas important to national defense in general and the Army. DEPSCoR is specifically designed to expand research opportunities in states that have traditionally received the least funding in federal support for university research. In FY07, academic researchers in Alaska, Arkansas, Delaware, Idaho, Kansas, Kentucky, Louisiana, Maine, Montana, Nebraska, Nevada, New Hampshire, North Dakota, Oklahoma, Puerto Rico, Rhode Island, South Dakota, South Carolina, Tennessee, US Virgin Islands, Vermont, West Virginia, and Wyoming are eligible to receive awards under this competition. The program provides the nation with a broad base, basic research infrastructure built on the single investigators within the current academic infrastructure. It thereby bypasses the high administrative burden often associated with large, resource intensive single focus efforts. Additionally, the program reflects remarkable flexibility and possesses a track record of innovation since the program is open to all topics described in the traditional Broad Agency Announcements (BAA) and is open to any researcher within the designated states. NSF state committees screen the proposals in the context of state research infrastructure needs and forward them to the services for final selection and funding. The work is consistent with the Army Science and Technology Master Plan, the Army Modernization Plan, and Project Reliance. In FY09, the Department of Defense awarded $14.1 million to 20 academic institutions in 14 states to perform research in science and engineering fields important to national defense. Of the total, the Army awarded $4.8 million to6 academic institutions in 10 states.

Defense University Research Instrumentation Program (DURIP) - DURIP supports the purchase of state-of-the-art equipment that augments current university capabilities or develops new university capabilities to perform cutting-edge defense research. DURIP meets a critical need by enabling university researchers to purchase scientific equipment costing $50,000 or more to conduct DoD-relevant research. The researchers generally have difficulty purchasing instruments costing that much under their research contracts and grants. The work is consistent with the Army Science and Technology Master Plan (ASTMP), the Army Modernization Plan, and Project Reliance. In mid-FY09, Department of Defense (DoD) made 222 awards to 107 academic institutions with awards ranging from about $50,000 to $1,000,000 and average $235,000. Of the total, the Army awarded 88 awards at $12.3 million with the average award being $139,000.

Historically Black College and Universities/Minority Institutions (HBCU/MI) - Programs for HBCU/MIs are a significant part of the ARO program. Historically, funding for the HBCU/MI Programs has exceeded $38M. In FY2009, this funding was impacted by the US Court of Appeals for the Federal Circuit ruling in the case Rothe Development Corporation vs. The U.S. Department of Defense and the U.S. Department of the Air Force. In brief, the court ruled that 10 U.S.C. 2323, the basis for set aside of funding for HBCU/MI Programs, was unconstitutional and therefore could not be used to fund such institutions exclusively. Programs administered on behalf of the Director of Defense Research and Engineering (DDR&E) were most severely affected. There were no solicitations for the DoD HBCU/MI Infrastructure Support Program or the Tribal Colleges and Universities Program. The Partnership in Research Transition (PIRT) Program, a planned second phase of the Centers of Excellence for Battlefield Capability Enhancements (BCE) Program was affected as well. Funding in the amount of $2.5M was received but was unable to be executed due to Rothe. The ARO (Core) HBCU/MI Program and the Centers of Excellence for Battlefield Capability Enhancements (BCE) programs are discussed below:

- **ARO (Core) HBCU/MI Program**: The ARO began its HBCU/MI program in 1980 with a $0.5 million set aside designed to encourage greater participation of HBCUs and MIs in basic research. The initiative has continued and in recent years has been funded at $1.2 million annually. These funds are made available to ARO scientific divisions as co-funding opportunities to support HBCU/MI research proposals submitted under the ARO broad agency announcement. In FY09 the ARO HBCU/MI program supported 26 grants and 4 conferences with a total value of approximately $2.2 million.

- **Centers of Excellence for Battlefield Capability Enhancements (BCE):** Established in FY04 by direction of the Department of the Army, the five BCE Centers of Excellence have proven effective in harnessing a critical mass of university research expertise and focusing intellectual capabilities on science and technology problems unique to Army. The objective is to transition advances resulting from basic research to technology demonstration as rapidly as possible. These projects take that approach one step further by partnering the university researchers with Army Training and Doctrine Command (TRADOC) Battle Labs

to gain first-hand perspective on the end-user's needs. Through these Centers, the Army user begins the collaboration with university researchers from the outset. The Centers will join with Army and industrial partners to accelerate the transition from research phase to actual technology demonstration. In addition, the Centers will recruit, educate, and train outstanding students and post doctoral researchers in science and technology areas relevant to Army Transformation. Although no FY09 funds were applied to this five-year program, research efforts carried over into the fiscal year and will soon terminate. The BCE Centers of Excellence and their respective research topic areas are:

- NC A&T State University – Environmentally Stable Flexible Displays
- NC A&T State University – Human Centric Command/Control Decision Making
- Tennessee State University – Sensor Fusion
- Prairie View A&M University – Beyond Line of Sight Lethality
- Tuskegee University – Flexible Extremities Protection

The Army Research Office continued administration of the DoD HBCU/MI Programs. Although the Rothe Court Decision pre-empted any new starts, research previously funded under the programs continued at HBCUs/MIs and Tribal Colleges and Universities. The John H. Hopps Scholars Program funded in FY08 continued to serve more than twenty Morehouse College Scholars.

Presidential Early Career Award for Scientists and Engineers (PECASE) – The PECASE program attracts outstanding young university faculty members, to support their research, and to encourage their teaching and research careers. PECASE awards are the highest honor bestowed by the Army to outstanding scientists and engineers beginning their independent careers. The Army traditionally nominates two young investigators for the PECASE awards, which average $200,000 per year for five years. In FY2009, ARO continued supporting PECASE investigator awards started in prior years and initiated fifteen new awards based on two important criteria: (1) innovative research at the frontiers of science and technology that is relevant to the mission of the sponsoring organization or agency, and (2) community service demonstrated through scientific leadership, education, or community outreach.

National Defense Science and Engineering Graduate (NDSEG) Fellowship Program
The ARO participates along with the ONR and the AFOSR in the NDSEG Fellowship Program, which is administrated under a contract managed by the AFOSR. With approximately $5 million available to the Army in FY09, the ARO selected 63 NDSEG Fellows who will begin their fellowships in the fall of 2009. NDSEG Fellows are provided full tuition and fees at any accredited university of choice and a stipend for three years.

YOUTH SCIENCE ACTIVITIES

Youth Science Activities - Whether it is providing a work/study experience, sponsoring tutorial classes during the summer, showcasing talented young high school scientists at symposia or judging student science fair projects, each of the Youth Science Programs sponsored by the Department of Army has one purpose in common – to increase the number of future adults capable of conducting research and development.

The Army's programs for the youth of this nation collectively reach more than 100,000 high school students throughout the United States, Puerto Rico and the DoD Schools of Europe and the Pacific. Students participating in the programs during this past fiscal year were awarded more than $380K in college tuition scholarships; savings bonds totaling in excess of $30K; and expense paid trips to international programs.

Additionally, 147students served as interns and worked in university laboratories during the summer with selected mentors. More than 500 students participated in programs that offered enrichment classes in science, technology, engineering and mathematics (STEM). Brief descriptions of these exciting and innovative programs follow:

The **Junior Science and Humanities Symposium (JSHS) Program** goals are to:

- promote research and experimentation in STEM education at the high school level;
- search out talented youth and their teachers, recognize their accomplishments at symposia, and encourage their continued interest and participation in STEM, and
- recognize publicly the accomplishments of these talented youths.

The **Research and Engineering Apprenticeship Program (REAP**) is designed to offer historically under represented high school students the opportunity to expand their background and understanding of scientific research. This is accomplished by offering the student an internship, during the summer months, to participate in a work/study atmosphere with a mentor in a laboratory setting. The experience serves to motivate the student towards a career in STEM by providing a challenging science experience that is not readily available in high school.

The **Uninitiates' Introduction to Engineering (UNITE) Program** is an aggressive and effective program that encourages and assists under represented students in preparing for entrance into engineering schools. High school students are provided the opportunity, during the summer months, to participate in college-structured summer courses which provide hands on applications, participation in lectures, problem solving as well as tours of laboratories and private and governmental engineering facilities. The students are introduced to ways in which math and science are applied to real-world situations and how they are related to careers in engineering and technology. Eight sites were funded this fiscal year, serving more than 500 students.

The **International Science and Engineering Fair (ISEF) Program** provides high school students the opportunity to present their projects, in competition with their peers, to Army judges who are special awards sponsors at these annual events. Each year, ROTC Units, Recruiting Battalions, Army Reservists and Army command/laboratory personnel serve as judges of student projects at more than 275 science fair competitions held throughout the United States and Puerto Rico. By participating in science fairs, the Army is able to encourage and stimulate talented students to consider careers in science and technology while simultaneously exposing these students to Army research and development opportunities.

The **Junior Solar Sprint (JSS) Program** is a new addition to the ARO Youth Science umbrella in FY09. The program provides 4-8th grade students in the northeast an opportunity to learn engineering and renewable energy concepts and apply them by building and racing solar cars. Students form teams in their local communities, build solar cars with the help of trained mentors, and race them in local competitions. Top winners from each local competition are invited to race in the Northeastern championship in Springfield, MA.

ARO SUPPORT TO ARMY TRANSFORMATION

THE IMPERATIVE TO TRANSFORM

The Army is continually evaluating and implementing approaches designed to meet today's challenges and prepare for the future. To be successful, the Army must transform to a force that will give it overwhelming capability in any and all situations, from insurgency to total war. The result will be a campaign-quality force with joint and expeditionary capabilities that will have relevant and ready land power available for combatant commanders and the Joint Force (focusing on coalition warfare, contingency planning, and combat operations conducted by the unified commands) activities. While achieving this, operational support to forces fighting the global war on terrorism and the exceptionally high quality of the all-volunteer force must be maintained. The 2004 Army Transformation Roadmap, updated with the 2007 Army Posture Statement, describes the path the Army is currently undertaking in the modification of its institutions and capabilities. This path defines the necessary changes required of the Army during time of war and in supporting joint/expeditionary capabilities — a set of tasks that will be successfully met through the balancing of current and future needs.

The Army is investing in critical technologies based on Future Force capability requirements (the maximization of joint interoperability, strategic transportability, and commonality of mission roles across services and locations) designed to spiral into the Current Force that will enhance immediate needs of the Joint Force. The Army's Science and Technology (S&T) Program is critical to development of the transformational capability envisioned for the Current Force and the Future Force. The S&T Program will provide core technologies and prototype systems targeted for the Future Force and also demonstrate innovative technology solutions that will enable leap-ahead or disruptive technologies that will transform current capabilities.

To accomplish the Army's mission in service to the Nation, continued efforts in all areas of research are necessary to meet the following requirements:

- Ensure full, timely, and sustained funding to be ready for current and future challenges
- Expand the size of the Army to build strategic depth and to enhance readiness across all components of the force
- Implement new policies to assure recurrent, predictable access to Army National Guard and Army Reserve units in order to meet sustained global demand for Army forces
- Enhance wartime authorities to improve commanders' ability to deal with emerging, in-theater operational demands and to build the capabilities of strategic partners
- Support to sustain our All-Volunteer Soldiers, their families, and our Army Civilians and to maintain the trust of the American people, whom we serve in this time of war and uncertainty

ARMY TRANSFORMATION STRATEGY AND ARMY CAMPAIGN PLAN

Transformation is a process that shapes the changing nature of military competition and cooperation through new combinations of concepts, capabilities, people and organizations. It employs the nation's advantages and protects against asymmetric vulnerabilities. It sustains the U.S. strategic position, thus helping peace and stability in the world. The Army's transformation strategy has three components: (1) transformed culture, (2) transformed processes, and (3) transformed capabilities.

The Army also is developing the right mix of force application capabilities required for modern conflict. At the same time, the Army is reorganizing its CS/CSS capabilities into modular packages. This will allow combatant commanders to more rapidly draw upon discrete Army capability modules. This process will create capabilities that provide the Joint Force with strategically agile and flexible arrangements of combat power.

The following are representative ARO-supported research programs that will support both the Interim Force and the Future Force.

ARO SUPPORT TO ARMY TRANSFORMATION

THE IMPERATIVE TO TRANSFORM

The Army is continually evaluating and implementing approaches designed to meet today's challenges and prepare for the future. To be successful, the Army must transform to a force that will give it overwhelming capability in any and all situations, from insurgency to total war. The result will be a campaign-quality force with joint and expeditionary capabilities that will have relevant and ready land power available for combatant commanders and the Joint Force (focusing on coalition warfare, contingency planning, and combat operations conducted by the unified commands) activities. While

achieving this, operational support to forces fighting the global war on terrorism and the exceptionally high quality of the all-volunteer force must be maintained. The 2004 Army Transformation Roadmap, updated with the 2007 Army Posture Statement, describes the path the Army is currently undertaking in the modification of its institutions and capabilities. This path defines the necessary changes required of the Army during time of war and in supporting joint/expeditionary capabilities — a set of tasks that will be successfully met through the balancing of current and future needs.

The Army is investing in critical technologies based on Future Force capability requirements (the maximization of joint interoperability, strategic transportability, and commonality of mission roles across services and locations) designed to spiral into the Current Force that will enhance immediate needs of the Joint Force. The Army's Science and Technology (S&T) Program is critical to development of the transformational capability envisioned for the Current Force and the Future Force. The S&T Program will provide core technologies and prototype systems targeted for the Future Force and also demonstrate innovative technology solutions that will enable leap-ahead or disruptive technologies that will transform current capabilities.

To accomplish the Army's mission in service to the Nation, continued efforts in all areas of research are necessary to meet the following requirements:

- Ensure full, timely, and sustained funding to be ready for current and future challenges
- Expand the size of the Army to build strategic depth and to enhance readiness across all components of the force
- Implement new policies to assure recurrent, predictable access to Army National Guard and Army Reserve units in order to meet sustained global demand for Army forces
- Enhance wartime authorities to improve commanders' ability to deal with emerging, in-theater operational demands and to build the capabilities of strategic partners
- Support to sustain our All-Volunteer Soldiers, their families, and our Army Civilians and to maintain the trust of the American people, whom we serve in this time of war and uncertainty

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INTERIM FORCE

Compact power generation through thermophotovoltaics and fuel cells

Improved engine performance through active control of dynamical processes

Enhanced combat information processor to solve information overload

Photonic band engineering for enhanced antenna performance

Designer propellants at reduced cost and increased safety

FUTURE FORCE

Human Dimension of Networks

Terahertz electronics for advanced communications

Multi-functional armor for future combat systems

Optical limiting windows for sensor protection

Smart rotor blades for enhanced rotorcraft maneuverability

Alternative KE penetrator materials

Chemical/biological vehicle shield

Genetically engineered material for biomolecular optoelectronics

All solid state FCS radar/illuminator/SATCOM OTM (K-band)

Flexible, light weight ballistic protection for the soldier

ARO CORE PROGRAM PROPOSAL ACTIONS

	RECEIVED	ACCEPTED	DECLINED	WITHDRAWN
Chemistry	72	62	29	3
Computing & Information Sciences	58	34	18	1
Electronics	59	35	11	0
Environmental Sciences	41	26	15	2
Life Science	72	33	20	1
Materials Science	53	37	10	4
Mathematical Sciences	38	26	15	2
Mechanical Sciences	60	26	28	0
Network Sciences	53	27	26	2
Physics	41	24	20	0
Technology Integration and Outreach	0	0	0	0
TOTAL	**547**	**330**	**192**	**15**

Note: The total of proposals accepted, rejected, or withdrawn does not equal the total received because proposals are not necessarily acted upon during the year of receipt. ARO proposal actions are the period 1 October 2008 through 30 September 2009. "Core Program" is defined as single investigator research (excluding special programs) supported with Army Project BH57 funds.

ARO FY09 FUNDING

CORE PROGRAMS	ALLOTMENT
Chemistry	$5,220,000
Computing Sciences Division	$4,246,081
Electronics	$5,491,200
Environmental Sciences	$2,579,594
Life Sciences	$5,459,994
Materials Sciences	$6,199,225
Mathematical Sciences	$3,296,478
Mechanical Sciences	$4,687,500
Network Sciences	$3,807,441
Physics	$5,648,713
SUBTOTAL CORE PROGRAMS	**$46,636,226**

SPECIAL PROGRAMS	ALLOTMENT
Senior Research Scientist Research Programs (Includes Directorate-level funding)	$1,071,442
National Research Council Associates Program	$148,643
Historically Black College & University/Minority Institution	$1,200,000
Army Supported High School Apprenticeship Program (HSAP)	$150,000
In-House Operations	$14,190,689
Subtotal Special Programs	**$16,760,774**
TOTAL PROJECT H57 FUNDS	**$63,397,000**

OFFICE OF THE SECRETARY OF DEFENSE (OSD) DIRECT-FUNDED PROGRAMS	ALLOTMENT
Defense Experimental Program to Stimulate Competitive Research	$4,753,000
Government Industry Collaborative University Research (GICUR)	$753,000
OSD Small Business Innovation Research/Small Business Technology Transfer	$750,000
OSD Historically Black Colleges & University/Minority Institutions	$0
OSD Chemical and Biological Defense Small Business Innovation Research	$2,043,007
OSD Chemical and Biological Defense Programs	$18,466,768
TOTAL OSD DIRECT FUNDS	**$26,765,775**

ARMY AND OTHER DIRECT FUNDED PROGRAMS	ALLOTMENT
Multidisciplinary University Research Initiative Program	$53,118,882
Presidential Early Career Awards for Scientists Engineers	$4,400,000
Defense University Research Instrumentation Program	$12,200,000
University Research Initiative Support	$1,653,333
MINVERVA	$2,829,785
Strategic Technology Initiatives (STI)	$375,000
Army Center of Excellence	$974,000
Institute for Collaborative Biotechnologies (ICB)	$10,724,000
HBCU/MI – Battlelab Centers	$2,646,000
Institute for Creative Technology (ICT)	$7,457,000
Institute for Soldier Nanotechnology (ISN)	$9,782,000
Board of Army Science and Technology (BAST)	$1,149,000
Small Business Technology Transfer (STTR)	$15,889,705
Small Business Innovation Research (SBIR)	$11,399,926
ARO-W Ballston Lease	$70,000
Youth Science Activities	$2,037,000
Research In Ballistics	$883,000
SBIR Support	$1,058,375
Economy Act Stimulus Funding - STTR	$223,000
DARPA (FY08 funds and FY09 funds received in FY09)	$100,922,306
Other Customer (Direct Cite and Reimbursable)	$202,939,222
TOTAL ARMY AND OTHER RDT&E FUNDS	**$442,731,534**

FY09 CONGRESSIONAL ADDS	ALLOTMENT
Center for Advanced Energy Storage Research and Technology	$1,595,000
Cyber Threat Analytics	$2,392,000
Fighting Drug Resistant Infections	$1,994,000
Global Military Operating Environments	$1,994,000
Nanostructured Materials for Photovoltaic Applications	$1,595,000
Perpetually Assailable and Secure Information System(PASIS)	$3,189,000
Lightweight Polymer Designs for Soldier Combat Optics	$1,162,000
Toxic Particles	$797,000
Center for Education in Nanoscience and Nanotechnology	$638,000
Development of Enabling Chemical Technologies for Power from Green Sources	$1,195,000
Manufacturing and Industrial Technology Center	$797,000
Academic Support and Research Compliance for Knowledge Gathering	$1,994,000
Self-Deploying Autonomous Sensor Platforms for Situational Awareness	$3,987,000
Direct Methanol Fuel Cell – Battery Recharger Program	$2,392,000
TOTAL FY09 CONGRESSIONAL ADDS	**$25,721,000**
TOTAL ARO FY09 PROGRAM	**$558,615,309**

SCIENTIFIC SERVICES PROGRAM

GENERAL INFORMATION

The Scientific Services Program (SSP) is implemented by a contract with Battelle Memorial Institute. The program provides a rapid means all DoD organizations and other government agencies to acquire Scientific and Technical Analysis Services (STAS) of scientists, engineers and analysts from small and large businesses, colleges and universities, academicians working outside their institutions, and self-employed persons not affiliated with a business or university. Through the SSP, these individuals provide the government task sponsors with scientific and technical results and solutions to problems related to research and development by conducting well-defined studies, analyses, evaluations, interpretations, and assessments in any technology area of interest to the government.

There were a total of 255 new SSP tasks awarded and 269 ongoing tasks were modified in FY09 adding scope and/or funding. The agencies served under the program and the number of new tasks awarded from 1 October 2008 through 30 September 2009 is shown in the table at the end of this section.

Examples of Tasks Awarded through the Scientific Services Program:

The SSP awards tasks in a wide variety of technical areas ranging from mechanical engineering to computer sciences, military personnel recruitment/retention to life sciences, and chemistry to material sciences. Again this year, in addition to the more traditional use of the program, new tasks were initiated to support the Warfighters & Combatant Commanders engaged in the Global War on Terror, Operation Iraqi Freedom, and Homeland Security.

The U.S. Army Research Office sponsored work included the study of strategic opportunities for basic research in new aspects of energy transformation to control and manage electrical energy (Task Control Number (TCN) 09111); an analysis and assessment of current and emerging chemical warfare agent decontamination and hazard mitigation technologies and the identification of knowledge and technology gaps (TCN 09192); Defense Threat Reduction Agency (DTRA) sponsored an ARO project on sensor integration, data processing and dissemination network to extend system capabilities and deployment of advanced, net-centric geographic information capabilities (TCN 09136); and, the Joint ARO/Defense Advanced Research Program Agency (DARPA) conducted a project to optimize warfighter protection and performance to gain new conceptual insights and understandings of biological systems and to exploit emerging systems technologies such as genomics, proteomics, and metabolomics that will help improve soldier physical and cognitive performance and reduce soldier mortalities (TCN 09070).

Research in support of weapon systems and equipment included tasks sponsored by: the Office of the Under Secretary of Defense for Acquisition, Technology & Logistics (OSD AT&L) sponsored a project to identify opportunities early in the RDT&E and acquisition process of major weapon systems and individual personnel military equipment to integrate system safety concepts and analyses to improve hazard mitigation throughout the life-cycle, thereby reducing preventable accidents and injuries (TCN 09169); U.S. Army Research, Development, and Engineering Command (RDECOM), Army Missile Research, Development & Engineering Center (AMRDEC) included a study of high-strength, low mass advanced composite materials for aviation, missiles and space applications materials and formulations, including nanomaterials, which could prove resistant to mechanical damage, and to investigate embedding nanosensor technologies that could permit the continuous monitoring of the condition of exploration launch vehicles and missile

motor casings (TCN 09177); Automotive Research, Development and Engineering Center (TARDEC) sponsored a task to develop new and innovative techniques for scanning of interior, exterior, components and assemblies of military vehicles to reverse engineer and develop CAD data that is needed for modeling and simulation analysis in areas for occupant safety, vehicle reliability, and energetics (TCN 09071); research in support of Army aviators was sponsored by the U.S. Army Medical Research and Materiel Command (MRMC), Army Aeromedical Research Laboratory (AARL) included a survey and assessment of developmental helmet mounted displays and systems, optical hardware, night imaging systems and protective eyewear (TCN 09107).

The U.S. Army Research Laboratory (ARL) sponsored tasks that included: evaluation of a low-cost commercial off the shelf ultra-wideband (UWB) scanning radar to detect armor-piercing roadside bombs that explosively form solid metallic penetrators (TCN 09105); a comprehensive evaluation of a nano-bio hybrid electronic platform for solar energy harvesting systems to accommodate the power demands and lessen the dependence on cumbersome batteries on future warfighters (TCN 09039); and, a study of dynamic fracture and fragmentation phenomena in brittle materials using a fully-coupled multiscale finite element code that can be applied to the survivability of tactical wheeled vehicles (TCN 09201).

Examples of work performed in the Chemical Sciences and Life Sciences technology area include the following U.S. Army MRMC, Walter Reed Institute of Research (WRAIR) tasks: a study of ballistic-like penetration brain trauma characterizing the changes in the expression profiles of functional proteins that may be involved in the brain injury cell death process and in the recovery of injured brain tissue (TCN 09162); and, a basic science and discovery investigation of immune response to combat trauma related wound infections to include novel therapies, novel methods, basic pathophysiology and diagnostics in response to clinical need and congressional interest (TCN 09061). The MRMC Army Medical Research Institute of Chemical Defense (AMRICD) performed work to characterize the molecular interactions of chemical warfare agents with biological systems using Nuclear Magnetic Resonance (NMR) spectroscopy (TCN 09267); and, the evaluation of medical countermeasures against chemical warfare agents in small animal models to characterize the onset, duration and recurrence of the seizures, extent of neuronal damage caused by CWA exposure and efficacy of neuroprotective therapies (TCN 09273).

The U.S. Marine Corps sponsored a task to provide systems engineering support to the Office of Secretary of Defense Joint Service Project Manager for Chemical and Biological (JPEO-CB) personal protective programs including: Joint Service Light Integrated Suit Technology (JSLIST), Joint Protective Air Crew Ensemble (JPACE), Joint Service Aircrew Mask (JSAM), JSLIST CB Coverall for CVC (JC3), Lightweight Chemical Biological Ensemble (LCBE), and future acquisition programs (TCN 09130).

The U.S. Navy sponsored an analysis and assessment of the Advanced Explosive Ordnance Disposal Robot System (AEODRS) which is scheduled to enter full-scale development in FY10 (TCN 09084); and, the Navy Personnel Research, Studies and Technology center sponsored a task to model how individual differences in cognitive ability and personality characteristics impact team process skill acquisition to allow the Navy to better classify sailors into optimal teams capable of operating high-technology warfighting systems and platforms (TCN 09058).

The U.S. Air Force Air Education and Training Command Personnel Center sponsored several tasks dealing with job classification, candidate selection, pre-deployment stress, behavior, and reliability (TCNs 09066, 09067, 09186, 09198, 09216 and 09220).

Number of SSP Tasks by Sponsoring Agency (FY09)

Activity*	Tasks
RDECOM	
AMRDEC	4
ARDEC	7
ARL	41
ARO	11
CECOM	1
CERDEC	2
ECBC	7
NSRDEC	16
TARDEC	9
Total	98
MRMC	
AARL	9
ICD	15
IID	1
WRAIR	26
Total	51

Activity*	Tasks
OSD	4
DoD	12
HQ DA	1
AMC	3
TRADOC	4
USACE	25
USN	24
USMC	1
USN/USMC	3
USAF	18
USCG	1
DHHS	9
DHS	1
Total	106
Grand Total	255

Acronyms & Abbreviations:

RDECOM – U.S. Army Research, Development & Engineering Command
- AMERDC – Army Missile Research, Development & Engineering Center
- ARDEC - Armaments Research, Development & Engineering Center
- ARL - Army Research Laboratory
- ARO - Army Research Office
- CECOM -
- CERDEC - Communications-Electronics Research, Development & Engineering Center
- ECBC - Edgewood Chemical Biological Center
- NSRDEC - Natick Soldier Research, Development & Engineering Center
- TARDEC - Tank-Automotive Research, Development & Engineering Center

MRMC – U.S. Army Medical Research & Materiel Command
- AARL - Aeromedical Research Laboratory
- ICD - Medical Research Institute of Chemical Defense
- IID - Medical Research Institute of Infectious Diseases
- WRAIR - Walter Reed Army Institute of Research

OSD - Office of Secretary of Defense
DoD – U.S. Department of Defense
HQ DA - Headquarters Department of Army
AMC – Army Materiel Command
USACE - U.S. Army Corps of Engineers
USN - U.S. Navy
USMC - U.S. Marine Corps
USAF - U.S. Air Force
USCG – U.S. Coast Guard
DHHS – Department of Health & Human Services
DHS – Department of Homeland Security

CHEMICAL SCIENCES

Designing Ion-Containing Nanostructured Polymers - Michael Hickner, Pennsylvania State University

The goals of this research are to define the molecular parameters of ionic block copolymers that impact selective transport and to develop structure-property relationships in order to provide a better understanding of the link between chemical composition, nanostructure, and transport. Two new polymers have been made: poly(hexyl methacrylate)-*b*-polystyrene-*b*-poly(hexyl methacrylate) and poly(perfluorooctyl methacrylate)-*b*-polystyrene-*b*-poly(perfluorooctyl methacrylate). During the next year, the investigators will work toward increasing the order in the copolymers through annealing using thermal and solvent methods and synthesizing block copolymer anion exchange membranes.

Engineering New Particles to Add New Properties to Films, Foams, and Emulsions - O. Velev, North Carolina State University

Dr. Velev is designing interfacially-active particles that can give unique properties/features to films, foams and emulsions such as stability, color, and specific rheological response. Particles based on hydrophobic cellulose that have strong absorbent properties have been synthesized under organic solvent-free conditions. The shape and size of these particles will be controlled by modifying the process parameters. Fundamental studies will be conducted to determine the affect of particle adsorption and interactions on the elasticity and rigidity of fluid interfaces. The thickness and stability of thin foam films formed between particle-loaded interfaces will also be investigated. It is expected that the results from this research will provide a potential solution to current break-down issues with foams and emulsions that are typically stabilized by surfactants. As a result, super-stable foams and emulsions can be produced that can then be incorporated into decontamination agents, catalysts, cleaning compounds, and absorbent particles.

Understanding Electrocatalysis in High pH Environment - S. Mukerjee, Northeastern University

The results from this research are expected to provide insight into the mechanisms of oxidation catalysts that function in alkaline environments. The 'Delta μ Technique' with X-ray absorption near edge structure (XANES) are the methods proposed for obtaining these results. This technique provides a surface rather than bulk material specific probe. The research, based on a year-long preliminary study, is expected to shed light on oxidation of C-C bonds in high pH environments. If successful, results from these experiments could lead to new fuel applications, such as directly using hydrocarbon fuels in alkaline fuel cells.

Study of Relocalization in Combustion Intermediates - Andrew Cooksy, San Diego State University

Dr. Andrew Cooksy is studying the phenomenon of relocalization in combustion intermediates. This phenomenon involves the process of combustion using unsaturated hydrocarbon fuels rather than the saturated hydrocarbons commonly found in petroleum. This research seeks to determine the relative importance of these relocalization isomers. The relocalization process will be studied in a combined spectroscopic and theoretical investigation. Relocalization isomers are connected by a vibronic pathway that redistributes electron density, altering orbital hybridizations and molecular geometry without changing the sequence of chemical bonds. Appearing in hydrocarbon radicals and carbenes, relocalization confers a structural ambiguity to these reaction intermediates that introduces a largely unstudied complexity to the chemical pathways of combustion. Professor Cooksy will present the results of his studies at a workshop entitled "Dynamics of Reactions with Multiple Mechanisms" in April 2010 at Argonne National Laboratory.

COMPUTING SCIENCES

Statistical Techniques for Detecting Internet Traffic Anomalies – Ioannis Paschalidis, Boston University

Motivated by objectives that include financial gain, information theft, and espionage, cyber threats have evolved from relatively simple viruses and worms into well crafted and targeted, multi-step, multi-level coordinated attacks over the past decade. The new class of intrusion methods is diverse, complex, and dynamic with a well engineered array of exploits and propagation mechanisms that evades standard defense mechanisms. Professor Paschalidis and his team have been investigating random and Markovian models for profiling and characterizing normal network traffic distributions and use that profile to detect deviations, or anomaly traffic. New statistical anomaly detection techniques combining inputs from several traffic anomaly detectors are being developed to monitor the aggregate Internet traffic associated with a group of computer systems and to detect spatial anomalies that could be used to identify a more global and coordinated attack scheme.

Defection & Response to Web Spam Attacks – P. Tan, Michigan State University

With the ubiquitous access to the Internet and the ease with which information can be created and disseminated through Web sites, a new form of Denial of Information (DOI) attack has surfaced to use the web medium to intentionally mislead, deceive, and spread erroneous messages with an attempt to undermine a user's ability to obtain reliable and accurate information. Professor Tan investigates novel techniques to verify the trustworthiness of social media web sites. A new co-classification framework is being developed to simultaneously detect web spam and spammers who are responsible for posting them on social media web sites. The framework will leverage out-of-domain

data collected from multiple social media web sites to improve classification performance.

Fluid Flow Model of Communications Networks – Donald Drew, RPI

This research explores the relationship between flows on networks and lattice gas models. It uses rules for interactions between particles at nodes to develop more sophisticated macroscopic equations for network traffic, similar to the Navier-Stokes equation for fluid flow. The resulting continuum analysis offers advantages that are not possible in the factorially driven discrete analyses. Applications are analyzing network flows with irregular topologies, the effect of switching and routing protocols on flow rates, and differing rules for interaction of the traffic units.

ELECTRONICS

Infrared and Terahertz Properties of Graphene – Elias Towe, Carnegie Mellon University

In its native and pristine state, graphene has a gapless band structure. However, a band gap can be opened if the crystalline symmetry is broken. Dr. Elias Towe at Carnegie Mellon University plans to alter the symmetry by creating holes in the structure ("antidot" structure). His preliminary calculations indicate that periodic structuring by lithographic patterning can open band gaps with energies that are within the infrared and terahertz range of the electromagnetic spectrum. His fabrication technique will involve e-beam lithography and consists of carving holes in the hexagonal unit cell as shown in the figure below. Once the structures have been fabricated, extensive optical measurements and characterization will be carried out to determine the suitability of the properties for sensing applications. These measurements will be correlated with theoretical modeling to achieve an understanding and hence determine trends to optimizing the structures for future use in infrared sensor applications.

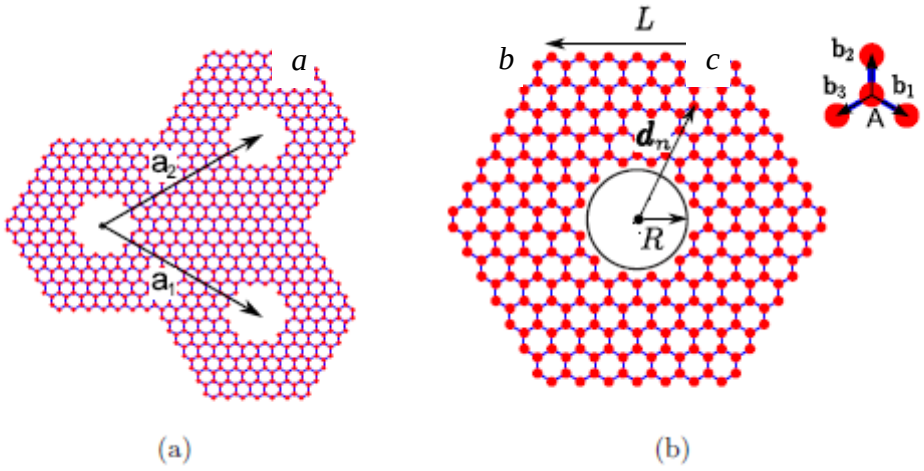

Figure 1. Graphene antidot lattice: (a) Lattice structure described by the basis vectors a1 and a2 (Ia1I = Ia2I = La□3); (b) hexagonal unit cell, with vectors b1; b2; b3 determining positions of nearest-neighbors of a carbon atom on sublattice A.

Terahertz Intracavity Spectrometer – Oliver Edwards, Zyberwear Inc

Mr. Oliver Edwards of Zyberwear Inc. is leading a new SBIR Phase II effort that seeks to develop a hand-held sensing and alarm system that utilizes intracavity laser absorption spectroscopy (ICLAS) and the resulting large effective optical path lengths (i.e., up to a kilometer) to realize detection capabilities for ultra-trace concentrations of chemical gases, biological aerosols and explosive vapors. This effort will build upon Phase I studies that suggest detection limits as low as 40 ppb can be achieved with the quantum cascade laser (QCL) based ICLAS design operating at 77 K and in a very short pulse mode (i.e., 2 ms pulse duration), and this will allow for detecting TNT vapors (i.e., 13 ppb) by increasing the pulse duration by a 3 (i.e., which can be accomplished by operating the laser closer to threshold and/or by operating at temperatures slightly below 77 K (i.e., which is possible using a Sterling cooler). It was also assessed that the proposed design and sensitivity would only require 6 mJ per spectrum measurement which suggests battery operation (e.g., 9 volt battery stores 16,000 J) is feasible. The Phase II effort will leverage collaborations with Air Force Research Laboratory, Hanscom (Dr. Buchwald) and the University of Central Florida (Professor Peale) to develop and demonstrate a very compact, low-power, and essential all electronic system that will in turn be applied to execute fundamental research to identify heretofore unknown vapor signatures (e.g., TNT).

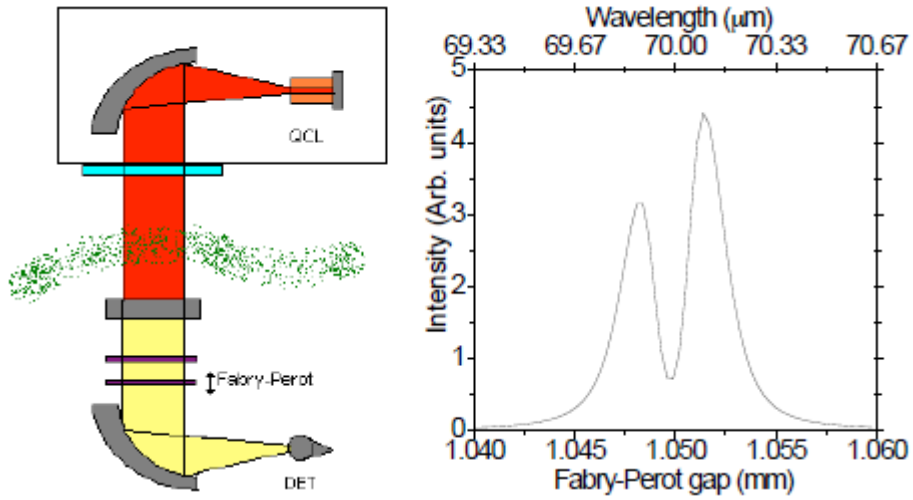

Figure 2. (Left) Schematic of QCL-based ICLAS system that uses a Fabry-Perot spectrometer to interrogate the laser spectrum. A vapor cloud passes inside the laser cavity. (Right) Recorded emission spectrum as a function of FP gap, which is directly convertible to wavelength as shown on the top axis.

Broadband Electric Field Sensor Array Technology – Ronald Reano, Ohio State University ElectroScience Laboratory

The proposed research will center on high quality-factor (Q) integrated electro-optical resonators, enabling sensitivities that are over an order of magnitude greater than existing polarization or interferometric modulation electro-optical field sensing schemes. The resonators will be developed in low-cost polymer and silicon photonic platforms incorporating nanoimprint lithography, a next generation low cost nanoscale fabrication technique, thereby avoiding costly compound semiconductors and exotic inorganic optical materials. A vector network analyzer (VNA) and tunable continuous-wave (CW) laser source will be integrated into the system to take advantage of the frequency resolution, bandwidth, dynamic range, and sensitivity of the VNA, as well as the low-cost and stability of the CW light source, enhancing the probability of acceptance of the technique as a diagnostic tool in the microwave test, measurement, and manufacturing industries. Only one high-speed photodiode is required for broadband sensing, through the design of resonators with slightly offset resonance frequencies. The use of integrated optics does not require bulky and expensive polarization optics, and once configured, eliminates the need for cumbersome and time consuming optical alignment. The proposed research supports the Intelligence, Surveillance, and Reconnaissance (ISR) and Command, Control, Communications, and Computers (C4) Future Force Technology Areas as defined in the 2007 ASTMP by enabling rapid evaluation of the operation of planar RF/microwave circuits and antennas for the multifunctional radio, radar, and sensor systems of the future. Professor Ronald Reano at the Ohio State University ElectroScience Laboratory will lead this new effort under the Army Young Investigator Program. His prior experience with the development of electro-thermal sensors using

mode-locked lasers and electro-optic semiconductors for the characterization of high-frequency devices for RF/millimeter-wave applications will help to advance this work to a proof of concept within three years.

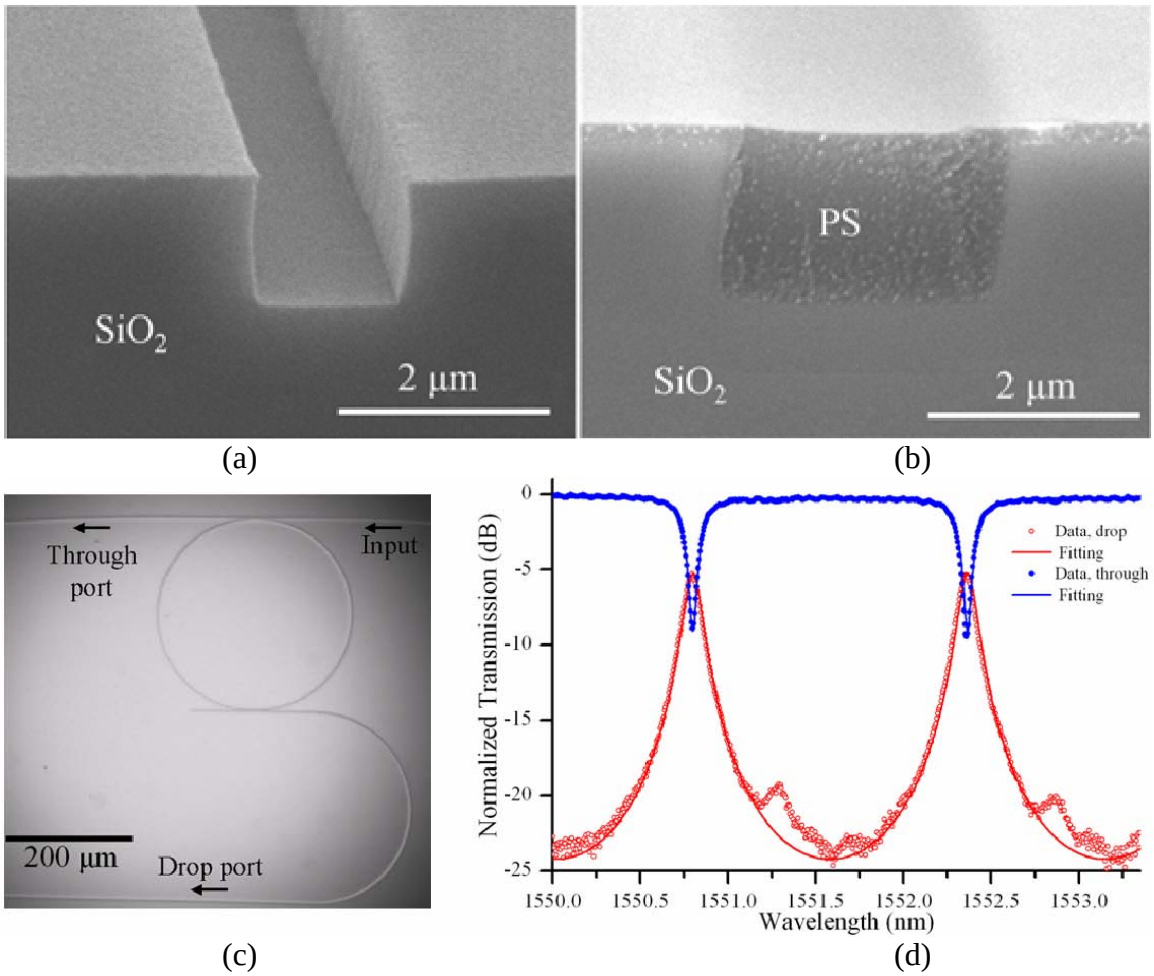

Figure 3. Components and test data for the broadband electric field sensor array under development by Professor Ronald Reano at The Ohio State University. (a) SEM of channel in SiO2 created using an isotropic plasma etching process and showing low surface roughness. (b) SEM of planarized polystyrene (PS) in the etched channel. (c) Optical micrograph of double-coupled ring resonator. (d) The measured transmission spectrum. The fitting parameters for air top-cladding are x = 0.92 (7.4 dB/cm loss) and y = 0.93.

Electrically-injected Microtube Quantum Dot Lasers – .Zetian Mi, McGill University

A short-term innovative research (or STIR) program has recently been award to advance novel semiconductor laser research into a regime where it will be usable for further development. Professor Zetian Mi at McGill University has been able to show optically pumped lasing from rolled-up "microtubes" with quantum dot active regions. Fabrication of the microtubes is based on an etching process which removes a layer below the

quantum dot active region and allows the thin sheet to roll up due to strain and form a microtube with diameters from 100 nm – 100 microns. Lasing occurs as the mode propagates in a direction similar to a rollercoaster with an upside-down loop. The input and output of the laser are thus in the plane of the substrate which the tube rests on. High Q cavities can be made to effectively lengthen the gain region by multiple passes through the loop (on average) before exiting the tube. Thus, such microtubes take up less real estate on the platform and still produce usable amounts of power. Another advantage of the lasers is that they can be made with multiple waveguides along their width which can define discrete wavelengths for use in WDM (Wavelength Division Multiplexing) systems. Such wavelengths can be developed with single longitudinal modes as in distributed feedback lasers very high bit rates. Another aspect of the work will be the addition of electrical contacts to form the first electrically-injected microtube lasers. Finally, the lasers are practical in the sense that they have been transferred to silicon for use with silicon electronics as on-chip interconnects. For most heterogeneous growths of III-V lasers on silicon, reliability is problem due to materials defects caused by strain through the buffer layers. In this case, the growth occurs on a III-V (GaAs) substrate and transfer of the laser can be done without strain interactions between the lasers and the post-transfer substrate.

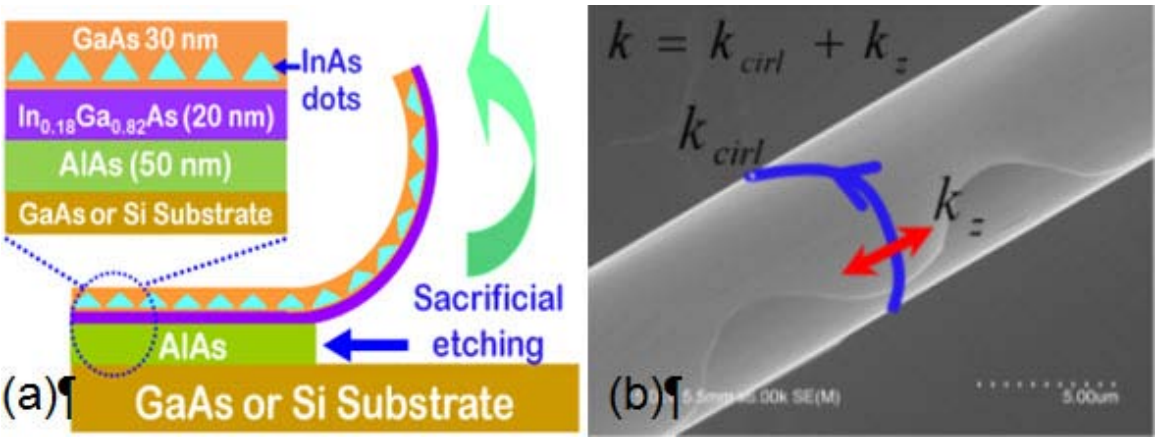

Figure 4. (a) Diagram of the epilayer heterostructure of the quantum dot microtube laser showing the InAs quantum dots with an In0.18Ga0.82As wetting layer and an AlAs release layer (b) SEM Micrograph of the quantum dot microtube after it has been rolled into a tube showing the optical mode propagation path around the tube and the lateral confinement structure.

Graphene Nanostructures for Novel Spin Magnetic Device Applications – Ki Wook Kim, North Carolina State University

Professor Kim's research will focus on theoretical investigations of the unique properties of graphene-based nano-structures for highly functional spintronic applications at room temperature. Graphene is a single atomic layer (or up to a few atomic layers) of carbon atoms arranged into a two-dimensional (2D) hexagonal lattice. Since its discovery in 2004, experimental data have revealed a number of unusual properties related to the

honeycomb carbon lattice that places graphene in the forefront of emerging carbon-based electronics. Professor Kim will analyze different device concepts that combine graphene layers in proximity with ferromagnetic slabs. Initially, two phenomena will be theoretically explored to introduce the desired spin magnetic functionalities in device structures with electrical control at room temperature. The first approach attempts to incorporate the magnetism by forming a hybrid structure with appropriate proximate magnetic materials. The second approach is to introduce magnetic effects (such as ordering), by utilizing non-zero magnetic moments induced at the edge states, such as defects and vacancies. Subsequently, he will pursue an analysis of carrier spin polarized transport in functionalized graphene layers in connection with bio-chemical sensor applications. Spin-polarized electronics, based on graphene layers, offers unique opportunities for manipulation of both charge and spin in nanoscale systems. These advantages are expected to bring revolutionary advances in information processing paradigms and memory technologies. The proposed research has potential impact on both memory and logic devices will that will enhance Army battlefield capabilities.

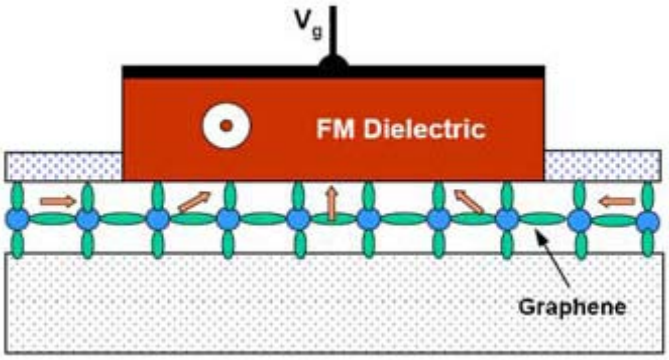

Figure 5. Schematic of a device structure having a graphene layer in contact with a magnetic slab, in this case, a ferromagnetic (FM) dielectric. The exchange interaction at the interface induces an effective magnetic field, causing the electron spin (red arrow) in the graphene layer to rotate.

ENVIRONMENTAL SCIENCES

Terrestrial Science

Hydrological research being conducted collaboratively by Virginia Tech, the St. Anthony Falls Laboratory of the University of Minnesota, and the USACE-ERDC Waterways Experiment Station and that is jointly but independently funded by ARO and the NSF Hydrologic Sciences Program, will develop and validate the first 3-D, unsteady state numerical model capable of accurately producing bridge foundation scour. The aim of the work is to integrate the latest developments in the numerical modeling capable of resolving 3-D coherent hydrodynamic structures of turbulent juncture flows with state-of-the art laboratory experimentation in which simultaneous measurements are made of instantaneous flow quantities and pressures within the progressive spatial and temporal development of a scour hole. Other fluvial hydrologic research will examine turbulent

flow and sediment transport in rivers near dike structures of various geometries through an integrated program of laboratory experiments, numerical modeling, and field application. The result will be a feasible design of dike structures that can effectively reduce sediment deposition and maintain a favorable flow condition during winter low flows in the island. Research at the Colorado School of Mines will be completed that is aimed at improving the way that DoD uses numerical modeling approaches and simulation in environmental restoration of present military installations and formerly-used defense sites contaminated by non-aqueous phase liquids through the development of systematic approaches to the calibration of the models used in such activities.

Collaborative research will be concluded between Duke University and the University of Melbourne in Australia that has been examining the fundamentals of force transmission, energy dissipation, and kinematics in deforming granular media across multiple spatial and temporal scales through laboratory experiments and numerical mode simulation and, based upon the results of this work, developing a new type of micromechanical models with predictive capabilities for multiscale phenomena in the solid-liquid transition regime. This granular materials basic research will provide the Army Corps of Engineers new micromechanical constitutive models of dry granular materials that, after experimental validation, will provide a computationally efficient alternative to DEM simulations, and fill an important niche in soil-structure/machine interaction systems modeling beyond the reach of current capabilities. Other terrain research will develop and test a new methodology for predicting the spatial distribution of soil thicknesses and erosion rates over geologic time scales, taking into account the climatic, lithologic, and topographic complexity of real landscapes, that will improve the Army's capability to model the hydrologic response of ungaged drainage basins and to quantify the natural 'background' rates of soil erosion at Army installations for comparison with modern rates.

Terrestrial Sciences research related to unmanned ground vehicles (UGVs) will develop new approaches to self-supervised mobility-based terrain classification that will generalize locally detected physical terrain features to remotely-sensed data in order to infer properties about mobility so that a UGV can autonomously navigate through its surrounding environment. Complementary research focused on vegetation sensing, using feature 'primitives' from multi-modal sensors that are commonly available on unmanned ground vehicles (UGVs) to classify vegetation and to create statistical models of UGV-vegetation interaction to better characterize movement pathways through vegetated terrain.

Sensor-related research will conclude that is directed toward combining laser induced breakdown spectroscopy (LIBS), short wave infrared (SWIR) and Raman spectroscopy, and developing state-of-the-art sensor data fusion algorithms to improve overall sensor performance. A new effort to create an EMI measurement system that can accurately measure the response of a buried target over a very broad frequency range for both very strong and weak targets and research to investigate a synthetic aperture acoustic technology that ultimately will have the potential to enable a vehicle-mounted active acoustic system will be completed. A fundamental investigation that combines cognitive

science and optical remote sensing, will address the optical detection, analysis, and interpretation of soil disturbance as it relates to combat tracking. Congressionally-directed GIS-based research will lead to improved land management tools and decision aids for the sustainable use of Army training and testing lands. Other Congressionally-directed at the Desert Research Institute will complete development of an integrated, predictive numerical model for forecasting terrain conditions and surface responses at different scales in desert regions to support military tactical operations, testing, and training, conclude research to understand the geomorphic controls operating on landscape systems as they relate to cultural resources management, threatened and endangered species habitat, and landscape erosion, and implement the concept of 'Master Environmental Reference Sites' for comprehensive characterization of soil processes that represent prevalent terrain conditions critical for military operations and testing (i.e., different military operating environments - MOE). Research being sponsored by Army and Marine Corps installations in the Mojave Desert of California will lead to lead to guidance to the military for translocation of endangered desert tortoises and a new 'head-start' approach to enhancing desert tortoise populations.

Atmospheric Sciences

In FY10, continuing research into the evolution of the nocturnal boundary layer structure and evolution in three distinct ways. One approach will use several Tethered Lift Systems with multiple sensor packages trailing from each. Each sensor package measures temperature, wind speed and direction, humidity, pressure, and the turbulent energy dissipation rate. The focus will be on quantifying the turbulent processes as a function of separation scales as well as the structure and dynamics of the interface of the surface layer and the residual layer resulting from internal gravity waves. Another approach examines the response of wind velocity with elevation induced by changes in surface roughness characteristics – urban to smooth to urban - using winds measured by paired Doppler wind lidars. The downstream effects of roughness change in speed, direction, and shear (vertical or lateral) will be quantified for the first time. Comparisons of observed effects with high resolution and/or operational models are planned. A third approach studies the directional meanderings of low speed winds (< 3 ms^{-1}) which spread airborne agents very differently than most dispersion models suggest. New insights into the spatial and vertical connections of coherent wind meandering in low speed conditions will be explored through the addition of highly resolved winds aloft using multiple sodars in existing field studies.

Military Habitation Sciences

The Environmental Sciences Division focus will be to extend development of Military Habitation Sciences in the areas of rapid start-up and stability of engineered biological processes, membrane processes for water purification, and resource reuse and transformation.

LIFE SCIENCES

Synthetic Biological Engineering of Photosynthesis - Pamela Silver, Harvard Medical School.

The goal of this project is to create a synthetic biology platform to directly use solar energy captured by cyanobacteria ("blue-green algae") to generate bulk amounts of chemical commodities such as fuel, fertilizer, feedstock preservatives, proteins, drugs and vitamins. Normally within these bacteria, captured light energy is converted to chemical energy which is then used via a series of enzymatic steps to synthesize carbohydrates or lipids for energy storage. Carbohydrate and lipid biomass can then be harvested, processed, and converted into biofuels via another series of enzymatic steps. The synthetic biology platform being developed aspires to eliminate the long series of enzymatic reactions involved in synthesizing and in subsequently degrading carbohydrates and lipids, and go directly from solar energy capture to biofuels. As a proof of principle, *Synechococcus* will be engineered to convert sunlight directly into biofuels, specifically hydrogen and biodiesel. A recent breakthrough discovery made in the PI's laboratory allows the investigators to control the flow of electrons for redox reactions in the cells. By modifying normal electron flow pathways, electrons will be guided directly from the photosynthetic apparatus within *Synechococcus* to a hydrogenase enzyme and will be used in the synthesis of hydrogen. Similarly, in other strains electrons will be directed from the photosynthetic apparatus to a newly engineered and introduced artificial metabolic pathway that will synthesize biodiesel.

DNA-tagged Nanoparticles for an Array of Biological Sensors - Hao Yan, Arizona State University

Dr. Yan's research efforts aim to achieve assembly of an array of nanoparticle sensors that could be used for biomolecule detection. In this system, DNA tags attached to the nanoparticles serve as address labels to direct the nanoparticles to specific locations on a DNA "pegboard." The ability to organize many different nanoparticles on the DNA pegboard, each responding to a specific biomolecule, will create a single array that can simultaneously detect a wide variety of biological targets. Dr. Yan's group has successfully designed and assembled DNA pegboards using a method that enables exquisite control of the location and organization of address sites. However, the attachment of a single unique DNA address label to a nanoparticle is extremely difficult using conventional methods, commonly resulting in the non-specific attachment of several tags to the nanoparticle. To overcome this obstacle, Dr. Yan has devised a novel method for attaching the DNA address labels to the nanoparticles. Each nanoparticle will be enclosed in a DNA container which holds a single DNA tag in a specific location relative to the particle (see Figure 6A). The researchers have successfully designed and constructed the DNA container, and will now enclose different nanoparticles and attach a unique DNA address label to each. Following removal from the DNA containers, the addressed nanoparticles will be incorporated into the DNA pegboard at their respective address sites which are designed into the array (see Figure 6B). The successful assembly

of the sensor array will enable the researchers to test the responsiveness of the system to biomolecule targets.

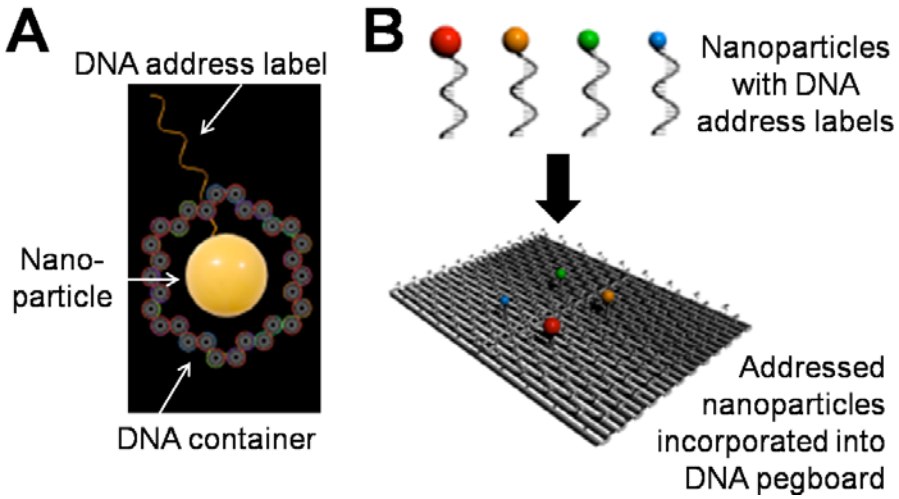

Figure 6. Nanoparticle sensor array: this array will ultimately be used to detect specific biomolecule targets; construction of the array involves (**A**) the assembly of nanoparticles enclosed in a DNA container that aligns the particle in a pre-defined orientation, and (**B**) assembly of the nanoparticles into the DNA pegboard at their respective sites as specified by the design of the array.

Remote Control of Intact Mammalian Brain Circuits Using Pulsed Ultrasound - W. James Tyler, Arizona State University

The investigator has developed a novel method of exciting cortical tissue, in essence the complement of repetitive Transient Magnetic Stimulation (rTMS; the current main thrust in direct brain modulation). Specifically rTMS acts to depress the cortical area in the field, but this ultrasonic method acts to excite it. Further, TMS is of limited use because it does not focus well and because it cannot be applied to deep structures in the brain. Ultrasound, by contrast, can be focused (in principle) with good spatial resolution at any depth in the brain, as demonstrated in preliminary experiments involving mice (see Figure 7). Reviewing the literature, it appears that this approach is both unique and essentially revolutionary. This investigator is the first person to demonstrate compellingly that ultrasound can activate neurons *in vitro* by "normal" ion channel mechanisms, and now he has taken the remarkable step of showing that it can work noninvasively *in vivo*. It evokes some of the interesting applications that were hoped for with microwave induction of hearing, etc. and may provide radical new ways to interface to the human brain. Using focused ultrasound, it may become possible to "touch" the exact neural circuits that govern specific cortical functions in a very specific, localized fashion and do it completely noninvasively with minimal side effects. Focused ultrasound stimulation of the human brain could enable a real science of consciousness, by allowing investigators to stimulate highly localized brain circuits while human subjects report their conscious experiences that result from the stimulation. Currently the

only way to acquire such data is through occasional experiments in the neurosurgery operating suite while humans undergo surgery for severe disease. While such reports have exerted an enormous influence on neuroscience, they will only be anecdotes until there are approaches that permit safe, extensive, noninvasive study. Focused ultrasound could be the answer.

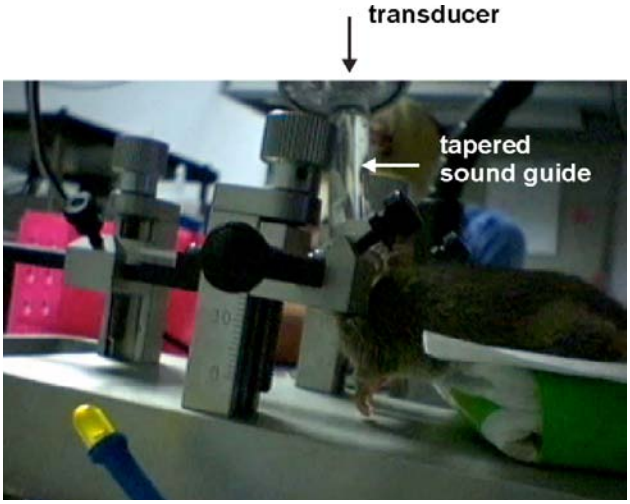

Figure 7. Low-intensity, low-frequency ultrasound can be used to selectively "touch" area of the brain through the intact skull (*i.e.*, noninvasively), sending an electrical message through the neural circuit and triggering movement in live mice.

MATERIALS SCIENCES

Self-Healing, High-Reliability Electrical Contacts – Pamir Alpay, University of Connecticut

Over the next year, researchers at the University of Connecticut will identify alloying additions to copper that will form inherently conductive native oxides under extended oxidation exposure. A combined experimental and theoretical approach is to be conducted, which will start with a thermodynamic analysis to identify possible alloying candidates, and then evolve into an alloy synthesis task that includes microstructural characterization, oxidation testing and contact resistance measurements of the candidate materials. The goal of the program is to identify a new contact alloy that will have self-healing properties and superior long-term electrical stability to the aggressive environments (especially chemical conditions) found on the battlefield.

Strain-induced Phase Transformations in Boron Nitride – Valery Levitas, Iowa State University

During the next year, unique samples of boron nitride with exceptionally well controlled order and texture will be utilized to establish a precise, and first-ever, mapping of strain-induced phase transformation. The results will both identify the requisite conditions to

induce phase transformation, and the nature (i.e., atomic structure and reconfiguration) of the structural transformations themselves. The effort will couple experimental and theoretical results to extract maximum information of phase transformations under compression and shear and establish new theory and simulations with unprecedented precision for the design of novel energy-absorbing materials.

Light-Assisted Assembly of Materials – Michelle Povinelli, University of Southern California

In the next year Professor Povinelli will demonstrate that spatially varying light fields produced above specially designed microphotonic templates can be used to guide the self assembly of complex multicomponent optical materials. Initial experiments will be performed on arrays of spherical dielectrics. The program will seek to carefully control the placement of both dielectric and metallic particles using both normal and guided resonance modes of light transmission through the template layers. The research will focus on determining how the template design affects the subsequent assembly of the particles. Electromagnetic simulations will be developed to model the forces driving the assembly process, and provide insights on specific optimized template designs.

Control of Single-Molecule Protein Conformations – H. Peter Lu, Bowling Green State University

During the upcoming year, unique single-molecule characterization tools will be utilized to demonstrate manipulation of protein conformations by force pulling a specific residue of a target protein. The overall goal of the program is to mechanically and optically control single-molecule protein conformations to explore unprecedented properties and capture exclusive states in real-time at an extreme molecular sensitivity. The work is motivated by the opportunity to manifest never-detected and unprecedented properties from proteins; if a random and transient (fluctuating) material property, typically non-detectable and lost as it is spatially and temporally averaged out, can be induced to appear at a specific frequency, then a novel property can be created from the material.

MATHEMATICAL SCIENCES

Realistic Simulation of Environments of Unlimited Size in Immersive Virtual Environments - Eric Bachmann, Miami University

Immersive virtual environments (VE) hold great promise for training, education, research, and entertainment. Unlike “desktop VEs” or “CAVEs,” immersive VEs treat the user’s body as an input device, and thus fully incorporate body-based (i.e., vestibular, proprioceptive, and efferent) sources of information. The incorporation of body-based information provides an intuitive and natural interface and has been shown to be critical for allowing users to maintain their orientation in the environment. To date, however, immersive VEs have had difficulty simulating large-scale environments (those requiring

extensive movement to apprehend) because they typically have a limited tracking area. Physical limits to the tracking area of immersive VEs generally arise because: (1) the user's HMD is tethered to a stationary rendering computer, (2) the tracking technology has a limited range, or (3) the lab only provides a relatively small tracking area. Prior work by this P.I. has increased effective scale of immersive VEs through successful development of Miami University's HIVE (Huge Immersive Virtual Environment). The HIVE was established in 2005 with funds from the U.S. Department of Defense and is currently the largest immersive virtual environment facility in the world. Housed in a 25 x 44 meter gymnasium, the HIVE is able to realistically simulate spaces such as an office complex or a ship interior at a one-to-one scale. Further work by the P.I. has involved the development of a self-contained inertial position tracking (SCIPT) system that does not rely on permanent infrastructure for position tracking. It is anticipated that further research along these lines will enable the next step in more realistic simulation, i.e., enabling immersive VEs to simulate environments of unlimited size, such as cities, suburbs, or national parks. Such a development will represent a quantum jump forward in the ability of VEs to simulate and train users for realistic situations in large environments. For example, soldiers could be trained in urban warfare in VEs that simulate an urban area of several square miles. Such simulations can also facilitate the training and evaluation of navigation and orienteering skills, as well as provide a valuable forum for interactive data visualization, command and control, or immersive teleoperation.

Stochastic Semidefinite Programming: Applications and Algorithms - K. A. Ariyawansa, Washington State University,

This project investigates approaches to solve stochastic semi-definite program (SSDP) problems. The SSDP class of problems generalizes conditions in deterministic semi-definite programs (DSDP) and both stochastic and deterministic linear programs. The broad aim of this research is to develop polynomial-bound algorithms to solve SSDP problems in both primal and dual formulations. Extensions to stochastic properties, even for small dimension problems, result in large scale computational sizes, easily increasing to billions of variables and constraints. Interest is focused on adapting interior point methods to assure good, practical performance. This work will add to the library of available optimization solvers and test data sets through the Network Enabled Optimization Software (NEOS) project of Argonne National Laboratory. These new algorithms will likely be suitable for parallel processing.

Modeling of Network Dynamics under Markovian and Structural Perturbation - A. Korzeniowski, University of Texas at Arlington; G. S. Ladde, University of South Florida

The research is concerned with a class of random dynamic networks subject to internal and external random perturbations. The system structure and dynamics are formulated in terms of finite graphs with one or bi-directional edges between the graphs nodes. Techniques involve probabilistic modeling of Network Reliability and Monte Carlo simulation. Proposed research deals with modeling of single and multiple agents under uncertain environments governed by *global dynamics*. The research team will formulate

and investigate time evolution of the following three new models of the state process, as follows:

- Internal Structure Dynamics Model
- External Structure Dynamics Model
- Mixed Structure Dynamics Model

Development will focus of novel methodologies for random dynamic networks with specific military applications to navigation in air/ground traffic, battlefield communication and signal control, all subject to random uncertainties. The problem formulation accommodates competitive-cooperative processes, multiple moving objects and logistics related to communication and transportation systems. Main focus is on characterization of feasible regions of operation and development of a framework for designing on line control laws that achieve performance objectives. First stage deals with closed form solutions when nodes act uniformly and independently while stage two will be devoted to complex systems. Third and final stage will address system stability under noisy perturbations. Employed concepts and methodologies include:

- *Invariant Sets* (reachable sets / safe and unsafe zones of operation)
- *Stability* (Lyapunov Methods / Semigroup Theory Techniques)
- *Complexity Characteristics* (uncertainty / decomposition-aggregation method)
- *Deterministic Versus Random* (error bounds / comparison)

One of the main obstacles is lack of closed form solutions which makes a direct analysis intractable. To overcome this, every possible attempt will be made to gain insight about the dynamics through simulation. Efforts are under way to seek closed form solutions. The significance of this project is summarized as follows:

- Characterizing *invariant sets (safe*/*unsafe zones*) and reachable sets (*target zones*)
- Finding *qualitative properties* (*almost sure asymptotic stability* and *stability*)
- Developing *stability conditions* (*rate coefficients* and *random shocks*)
- Estimating *dynamic reliability* of the multi-agent system

The approach yields direct benefits toward multi-agent systems. Namely, invariant sets allow avoidance of unsafe zones while utilizing exclusively safe zones operation mode.

MECHANICAL SCIENCES

A Study of Supersonic Compression Corner Interactions Using Hybrid LES/RANS Models – Jack R. Edwards, North Carolina State University

This research project has been focused on the development of a new strategy for blending Reynolds-averaged Navier-Stokes (RANS) and large-eddy simulation (LES) turbulence closure strategies. The new method utilizes a ratio of turbulence length scales, based on

modeled and resolved expressions for the turbulence kinetic energy, to define a blending function that shifts the closure from RANS near solid walls to LES further away. The method is more universal than previous efforts, in that a single problem-independent model constant is used. This approach has been tested for an array of compressible boundary layers at different Reynolds numbers. In a related study, an older LES/RANS model has been applied to a smooth compression-corner shock / boundary layer interaction to assess its ability to capture the amplification of turbulent fluctuations. The model accurately captures the evolution of Reynolds axial and normal stresses but fails to capture the level of amplification of the Reynolds shear stress. Techniques for extracting turbulence statistics that mimic those used in hot-wire anemometry have been developed and applied. In the next year Edwards plans to finish the development and testing of the new LES/RANS model. This will include completing the sensitivity studies and comparing the results of the new model to available experimental data.

Advanced Composite Armor: In Situ Sensing with Carbon Nanotube Networks for Improved Damage Tolerance – Tsu-Wei Chou, Department of Mechanical Engineering and Center for Composite Materials, University of Delaware.

The ability to conduct real-time in situ state sensing and health monitoring has tremendous significance in military operations in terms of evaluating operational availability and survivability and also in terms of post-event damage assessment. One potential solution to this challenge is to use carbon nanotubes as a network of sensors in a traditional laminated fiber composite. Those nanocomposites then enable the detection of deformation and damage using electrical techniques. Professor Chou's research approach is to process SC-15 epoxy-based glass fiber composites with a highly uniform dispersion of carbon nanotubes as an electrical conductive network. Then, he will characterize the damage sensing capability of the hybrid composite under static and dynamic loading through both analysis and modeling in 3D and experimentation. Accomplishments to date include fabricating nanocomposites using a calendering technique and developing a 3D model of the nanotube networks including identifying the contact status between neighboring nanotubes. During the upcoming year, the project will pursue optimization of the nanocomposite structure (using carbon nanotubes, UD S-2 glass fibers and SC-15 epoxy composites) and identification of its electrical percolation threshold. Static and dynamic testing will track the resistance response of the composite and provide evidence of damage mechanism evaluation. Analysis and modeling will explore the use of Monte Carlo methods to model the electrical percolation thresholds of the nanotube networks as well as the prediction of effective conductivity of the composites. In addition, the project will develop efficient algorithms for 3D backbone identification.

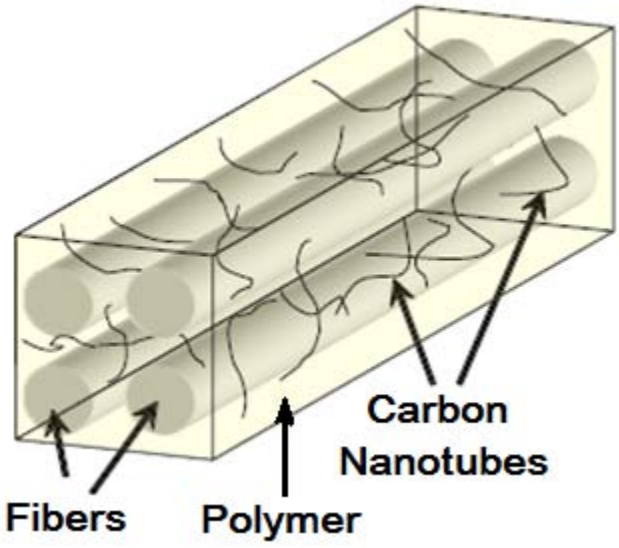

Figure 8. Nanocomposite content and structure.

Performance and Strength of Low Density Advanced Materials - Rashid K. Abu Al-Rub, Texas A&M University

In the last few years, many studies have focused on manufacturing nanocomposite materials that have mechanical properties superior to the traditional composites. Nanocomposite materials are materials reinforced with sub-micron and nano particles (e.g. metallic, ceramic, and/or clay particles, carbon nano fibers, carbon nanotubes, etc). It is claimed that the size of micro/nano-particles and their interfacial strengths have significant effects on the ability of nanocomposites to resist ballistic damage. However, very few studies have focused on the effectiveness of these new composites on resisting impact damage. Therefore, the main goal of this research is on assessing the ballistic damage performance and strength of those advanced materials through integration of non-classical theoretical and multiscale computational developments. The current classical continuum mechanics theories, which are good for micro-composites, are not applicable to describe the strength and damage response of nanocomposite materials since they cannot predict size-scale effects (i.e. smaller is stronger). Therefore, the focus of this research is on the development of a non-local theory and multiscale computational framework that can bridge this gap and that can be used in guiding the design of better ballistic damage-resistant nanocomposite materials.

Another crucial problem that will be solved through the development of the non-local theory is obtaining mesh-independent predictions of the ballistic limit (i.e. the minimum projectile velocity for complete perforation) when using an existing finite element software or hydrocode in simulating high-speed impact damage. Army scientists and engineers still have difficulty predicting the ballistic limit velocity in penetration events independent of the finite element mesh.

From economical (time and costs) point of view, performing straightforward macro-micro experimental measurements on a number of material samples of different sizes, for various microstructural, geometrical, and physical phase properties, and volume fractions under hypervelocity impacts/blast loading conditions on nanocomposite materials is a hardly feasible task. Therefore, the objectives of the proposed research will be achieved through the development of multiresolution (multi-scale) hierarchical non-local constitutive models and computational frameworks that can be used effectively in assessing the ballistic damage performance of nanocomposites and guide the design of their micro/nano-structure. This non-local framework incorporates material length scale parameters into the classical continuum mechanical theories allowing one to predict size effects. Therefore, the novel feature of the proposed research is on pushing the limits of continuum-based theories to predict the mechanical behavior at the micron, sub-micron, and nano length scales without the need to perform computationally expensive atomistic or molecular dynamics simulations. Moreover, the proposed non-local theories can overcome the problem of mesh-dependency when simulating ballistic damage performance and can yield meaningful and well-posed predictions.

Until now there have been very few attempts to perform multiresolution simulations of ballistic damage of nanocomposite materials. Therefore, the application of the multiresolution analysis to design of revolutionary ballistic-resistant materials is another novel feature of the present project.

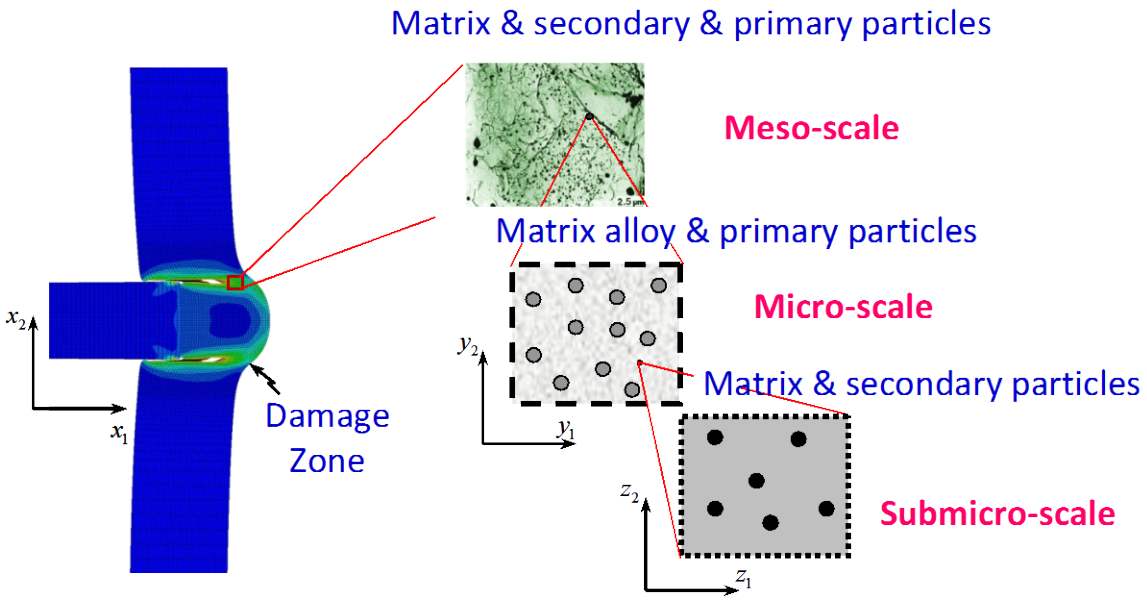

Figure 9. Illustration of multiresolution (multiscale) framework to model the evolution of micro-damages (micro-cracks and micro-voids) at different nested length scales.

Autoignition and Combustion of JP-8 and its Surrogates at Moderate Pressures – Kalyanasundaram Seshadri, University of California at San Diego

The objective of this research is to develop surrogates that can describe the combustion of JP-8 in laminar flows employing counterflow configuration at values of pressure between 1.013 bar and 25 bar. The investigation will include nonpremixed combustion, premixed combustion, and spray combustion. The major components of JP-8 are straight chain paraffins, branched chain paraffins, cycloparaffins, aromatics, and alkenes. JP-8 and candidate surrogates for JP-8 will be examined. An experimental facility has recently been built and is currently being completed for carrying out experiments at pressures between 1.013 bar and 25 bar. Critical conditions of autoignition and critical conditions of flame extinction at pressure will be measured. To characterize the structure of the reactive flow field, temperature profiles, and concentration profiles of stable species will be measured. Detailed chemical-kinetic mechanisms and reduced chemical kinetic mechanisms that describe autoignition and combustion of the surrogates will be developed and validated against the experimental data. The final outcome of this research will be surrogates that can be used to describe autoignition and combustion of jet fuels under nonpremixed conditions and premixed conditions. The research will provide insight on mechanisms of autoignition of JP-8 in flow systems, and will elucidate the influence of flow and pressure on combustion of JP-8 and surrogates for JP-8. The ultimate outcome of the work will be a list of surrogates that reproduce key aspects of combustion of JP-8.

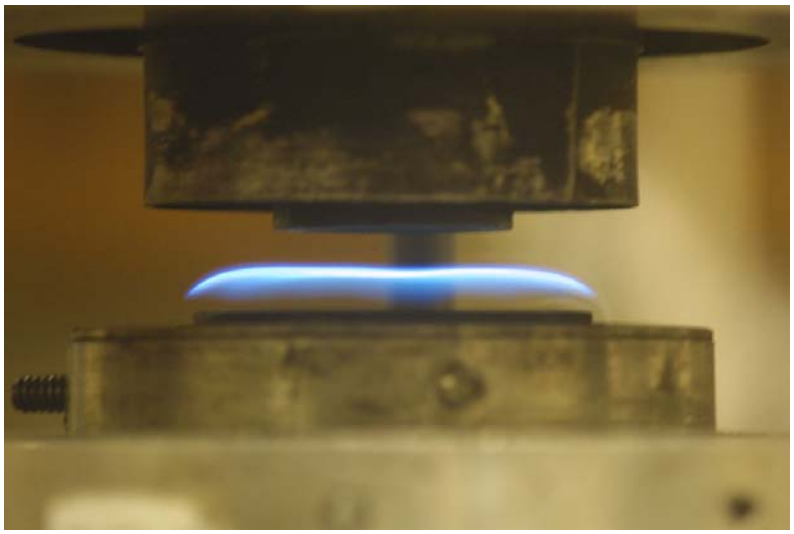

Figure 10. Flat flame burner used to determine detailed fuel kinetics via flame strain extinction and ignition.

NETWORK SCIENCE

Cognitive Radio for Tactical Wireless Communication Networks - Mike Pursley, Clemson University

Cognitive radios adapt to the current communication channel conditions to improve network performance. If cognitive radios are provided with the right protocols, they have the potential for more than an order of magnitude improvement in throughput compared with conventional tactical radios. Dr. Pursley will investigate the use of different protocols in different channel conditions in the context of cognitive radio, including effects of fast fading and other high rate variations of the channel. Using this knowledge, statistical learning techniques will be investigated to permit cognitive radios to select or adjust the intervals used in the adaptive protocols for modulation selection, initial power adjustment, and adaptive transmission.

The Role of Channel Distribution Information in the Interference Management and Network Performance Enhancement - James Zeidler, University of California, San Diego

One of the fundamental challenges in exploiting the additional spatial processing gain provided at the physical layer by multiple antennas is the knowledge of the channel state, which is needed to use beam-forming in the upper layers for routing and scheduling. Typically, channel state information is measured at a given time instant, which does not give an indication on how the channel is varying over time. Professor James Zeidler will investigate the use of the channel distribution information (CDI) to maintain stable beamforming vectors over a time scale defined by the rate at which the channel spatial correlation matrices vary in time. The CDI will be used to limit the amount of power that must be transmitted between nodes to improve overall network performance by maintaining stable beamforming vectors over the time scales defined by channel statistics rather than the reduced time scale associated with the channel coherence time.

Stochastic Networks for Coherent Decision Making - N. Singpurwalla, George Washington University

The objective of this research is to enhance the science base underlying the stochastic aspects of network reliability and survivability. The main thrust areas of research are twofold. One is to endow networks a dynamic character; the other is to incorporate interdependencies between the network's nodes and links in a hierarchical manner. The former calls for the solution of a new class of stochastic differential equations. The latter requires the generation of new families of distributions on a unit hypercube.

Supplementing the proposed work, but integral to it, are two topics that contribute to the science base of socio-cultural modeling via the dynamics of social networks by a coupled system of stochastic differential equations and the quantification of trust and selflessness, topics that are germane to current issues of defense and national security. Co-operation in networks entails the notion of trust among the nodes and links and this entails the

mathematics of tracking, updating, pooling and utility elicitation for optimal decision making in a socio-cultural, psychological, and neurological contexts.

Strategic State Estimation in Uncertain and Mixed Multiagent Environments- P. Doshi and A. Goodie, University of Georgia,

In this project, three empirical studies will examine probability judgment in simulated UAV settings within the Georgia Testbed for Autonomous Control of Vehicles to identify predictive models or their combinations that best account for assessed probabilities. In many psychological studies, even where correct predictions are motivated by material incentives, participants do not report subjective probability assessments honestly. In settings that are not constructed to prevent it, participants may have stronger motives to express extreme confidence, considerable uncertainty, or other socially desirable probability expressions, instead of their true belief. During the first year of the project will test the utility of various proper scoring rules, under which, if p is one's true belief of a probability, expressions of p result in superior expected outcomes than any other expression, in increasing the coherence and correspondence of confidence assessments. The study will establish the validity of and help model the probability judgment of humans engaged in an adversarial role expected in UAV operating theaters, and will provide critical data for formulating the behavioral models of significant role players in a UAV's operating theater. Additionally, this extends the research of human-computer interaction to a UAV domain, and it promises robust solutions to the complex problem of accounting for both an operator's cognitive biases and the biases of an adversary.

System Reliability-Based Design Optimization under Input and Model Uncertainties - Kyung Choi, University of Iowa

An increasingly competitive global market demands product designs that can be uniformly relied on to demonstrate consistently high levels of performance under a wide range of operational conditions without being subject to unanticipated failure and with substantially reduced maintenance requirements. New technology and numerical methods will be developed for system-level reliability-based design optimization (RBDO) with the associated target confidence level under these input and simulation model uncertainties. Important technical developments will be made in the area of validation and verification. To assess the confidence level of the simulation model for RBDO, a design-driven validation & verification (V&V) method will be developed using a Gaussian stochastic process to estimate the measurement error and construct the prediction of the simulation model. The challenge is to develop and integrate the design-driven V&V method with the RBDO process to obtain a reliable design with the associated target confidence level. The most probable point (MPP)-based dimension reduction method (DRM) provides an accurate inverse reliability analysis without requiring second-order sensitivities like the second-order reliability method (SORM)

Learning in the Presence of Unawareness - Joseph Y. Halpern, Cornell University

Current approaches to decision theory and game theory implicitly or explicitly assume that the game/decision problem is, in a sense, completely understood. But in a complex decision problem, it is far from clear what the state space is; and in a complex game, a player may be unaware of what moves he or another player can make (and may even be aware of this lack of awareness). For example, in a war scenario, an enemy may not be aware of what weapons the US has developed recently, but may realize their lack of awareness. This project focuses on learning in the presence of unawareness. Specific issues of concern are how beliefs should be updated as a result of learning unanticipated information (which was not originally modeled in the state space), learning in the presence of ambiguity (where different agents interpret the same notion—such as "security"—in different ways), the role of information revelation (where one agent reveals to another the possibility of a move of which he was previously unaware), and repeated games with awareness.

PAGE: Policy Analytics Generation Engine - V. S. Subrahmanian, University of Maryland,

Lately, there has been a plethora of work on socio-cultural modeling of various types of groups including foreign political organizations, insurgent groups, terror groups, or investor groups. However, an important problem centers on how to influence these groups. For instance, what actions can US policy makers recommend that maximize the chances that the group will either take some actions we would like them to take or prevent them from taking an action we do not like? The PI will develop a formal theoretical framework and associated algorithms within which analysts can state their policy goals, with respect to a specific cultural group, and have algorithms automatically suggest options on a course of action (with a probability assessment of achieving the goal).

Efficient Algorithms for Computing Stackelberg Strategies in Security Games - Vincent Conitzer, Duke University

Game theory provides a powerful and expressive framework for modeling a wide range of security and defense problems. This project focuses on a special type of strategies for games, called Stackelberg strategies. Stackelberg strategies are optimal when one player (the leader) has the advantage of being able to commit to a (possibly randomized) strategy before the other player moves. For example, a defensive unit can commit to a randomized patrolling pattern to deter attacks; and a convoy can commit to a randomized strategy for choosing a route to discourage attacks on it. Such commitment offers several advantages. First, it can increase (and will never decrease) the leader's utility. Second, Stackelberg strategies can be easier to compute than Nash equilibrium strategies, and avoid equilibrium selection problems. Third, it reduces the need for secrecy about the leader's strategy. This project employs techniques from computational complexity analysis, convex duality, constraint generation, and graph algorithms to explore new computational approaches for efficiently finding Stackelberg strategies in realistic

domains with exponentially large strategy spaces. Potential impacts of this research include increased ability to compute optimal commitment strategies for security and defense scenarios, enabling more effective (lower cost/less risk) strategies for defending U.S. assets.

Probabilistic Tracking and Trajectory Planning for Autonomous Ground Vehicles in Urban Environments - Mark Campbell, Cornell University

Current and future Army and DoD missions will require autonomous robotic systems for supply missions, information collection, decision aids, and warfare support. The PI will develop a unified theory for perception and planning in autonomous ground vehicles. Because of the complexity of the problem, the PI will focus his efforts at the lowest level: detection, tracking and classification of obstacles in the environment, and trajectory planning and control of the robot based on the former. The PI will develop new techniques for robust tracking/perception so as to enable reasoning and planning based not only on what is happening at a given instant in time, but also based on reasonable expectations of what will happen next.

Real-Time Identification of Wheel Terrain Interaction Models for Enhanced Autonomous Vehicle Mobility - Alonzo Kelly, Carnegie Mellon University

The Army of the future will rely heavily on autonomous vehicles. Autonomous vehicle research has continuously demonstrated that a platform's precise understanding of its own mobility is a key ingredient of competent machines that perform. Agile autonomous mobility relies fundamentally on understanding and exploiting the interactions between the terrain and tractive devices like wheels and tracks. The PI will find a way to calibrate the specialized faster-than-real time models which are ubiquitous in unmanned ground vehicles. The PI will develop techniques to improve the accuracy of predictive models which are the key enabler for high performance unmanned ground vehicles.

PHYSICS

Disorder in Optical Lattices - Brian DeMarco, University of Illinois Urbana-Champaign (UIUC).

The disordered Bose Hubbard (DBH) model is a paradigm in condensed-matter physics describing strongly-interacting, disordered Bosonic systems (*i.e.*, systems composed of bosons that, in contrast to fermions, can have the same energy and occupy the same place in space). Despite being applied to many materials—from superfluids in porous media to superconducting thin films—questions remain regarding some of the most basic features of the DBH model. Brian DeMarco's group at UIUC is presently the only group that can add fine-grained disorder to a 3D optical lattice in a way described by the DBH model, and they are using measurements on this system to examine some of these outstanding issues. Fine-grained disorder is superimposed on a cubic optical lattice using laser speckle generated by a diffuser which randomly scatters the light. Atoms experience a

potential energy shift proportional to the intensity of the green laser light, leading to a combined potential that is a disordered lattice potential. The average potential energy shift change from the speckle field is used to quantify the disorder strength, which can be continuously tuned from zero to the regime of strong disorder.

Based on theoretical and computational studies, three mutually-conflicting phase diagrams have been proposed for the DBH model. These proposed diagrams are qualitatively shown in Figure 11. Dr. DeMarco's group is working toward experimentally mapping the phase diagram of the DBH by emulating it in the disordered optical lattice described earlier. The team is able to determine the phase in which the system at particular disorder strength, the on-site interaction strength, and the site-to-site hopping energy by measuring mass transport after "kicking" the atoms in the optical lattice. Current results have shown that sufficient disorder changes the system's phase from superfluid to insulating. These observations rule out the class of phase diagrams described by Figure 11B.

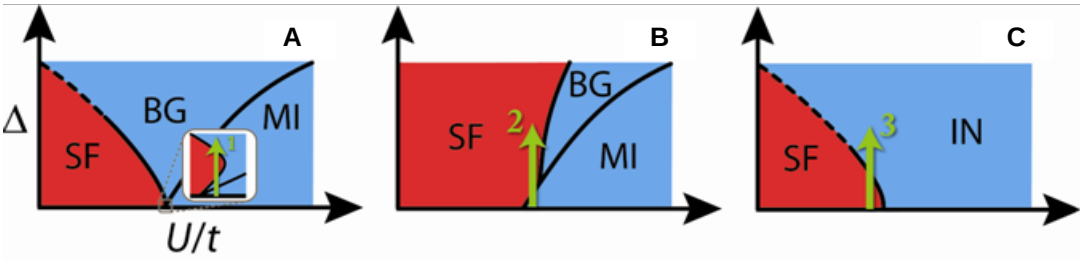

Figure 11. Three diagrams proposed to represent DBH model: phase diagrams (**A**), (**B**), and (**C**) were each proposed to represent the DBH model but provide mutually-conflicting descriptions. The phase diagrams show four phases: superfluid (SF), Bose glass (BG), Mott insulator (MI), and insulator (IN) as a function of the disorder strength (Δ), and the ratio of on-site interaction strength to the energy required for an atom to hop from one site to the next (U/t). Researchers funded through ARL/ARO have ruled out model B, but the remaining models will be tested in FY09.

Because there are two classes of insulating phases, new techniques must be worked out to distinguish them; mass transport measurements are not sufficient. The team is working toward measuring compressibility of atoms in the disordered lattice locally. Combining this information with the transport measurements will enable the team to map the entire phase diagram of the DBH model thus answers a long-standing question in the field. Accomplishing this task will further confirm optical lattices as a powerful tool for obtaining answers to some computationally intractable problems.

Three-Dimensional Fermi-Hubbard Model – Randy Hulet, Rice University

A major opportunity sought in research with optical lattices is the ability to map experimentally the phase diagram of theoretical models. A variety of theoretical models have been developed to describe various states of matter (*e.g.*, superconductivity, insulating phases, etc.). However, for a number of these models, the conditions at which these phases of matter would exist as predicted by the model cannot be calculated. When

such a model is the leading and best explanation for a known material phenomenon, it becomes a sort of collective quandary: is the model correct or not? Such is the case with high temperature superconductivity, discovered in the 1980s. To date, a theoretical understanding of this phenomenon does not exist. The leading model is the two dimensional Fermi-Hubbard model. Unfortunately, the phase diagram for this model is not calculable, so it is unknown whether it leads to superconductivity or not in the regime of interest.

Here, optical lattices provide a very desirable opportunity. An optical lattice refers to an ultra-cold atomic gas in which the atoms are subject to a one, two or three dimensional standing wave potential generated by lasers. An optical lattice can be designed according to the operator's wishes—to emulate a specific model. Because it is an accessible system, the phase diagram of the system can be probed experimentally. When one cannot calculate the phase diagram of a particular theoretical model, it can be experimentally measured with an optical lattice. This is the overall goal of the quantum emulators program supported by ARO and DARPA. An essential milestone toward achieving that goal is to verify the approach by mapping known phase diagrams of specific models. The three dimensional Fermi-Hubbard model at half filling is one of these. In this model, with the lattice half filled, the magnetic moments of the particles will order, alternating directions from particle from particle.

Dr. Hulet's team at Rice University is close to achieving this intermediate goal. Two experimental techniques are being developed to do so. First, the generation and loading of the optical lattice must be complete. The generation of the optical lattice has been accomplished and the team will soon implement a new cooling scheme that will adequately trap the lithium atoms (^{6}Li) in the lattice. Second, a Bragg scattering technique for detecting the antiferromagnetic ordering is being implemented (see Figure 12). The combination of these two approaches is anticipated to verify the ordering of the 3D Fermi-Hubbard model and set the stage for the team to begin probing the unknown: the 2D Fermi-Hubbard model phase diagram, particularly with doping.

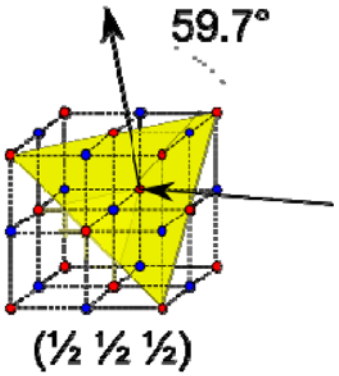

Figure 12. Bragg scattering of light off a plane of like magnetic moments (yellow triangle). The lattice will be a standing wave of light with ^{6}Li atoms in the valleys of the standing wave. Ordering results from interactions between the atoms at different sites.

Attosecond Pulses - Margaret Murnane, University of Colorado; Zenghu Chang, Kansas State

Modern ultrafast laser technology has revolutionized spectroscopy by making it possible to generate coherent light pulses (as short as tens of femtoseconds long) spanning the infrared and visible regions of the spectrum. Using nonlinear frequency conversion or continuum generation techniques, perfectly synchronized pulses covering a broad range of the spectrum can be generated for a range of pump-probe molecular spectroscopies, including transient absorption spectroscopy, nonlinear four-wave mixing spectroscopies, Coherent Anti-Stokes Raman microscopies and spectroscopies, and novel two-dimensional spectroscopy. These new tools have uncovered insights into the function and dynamics of molecules, as well as enabling advanced ultrasensitive molecular sensing schemes relevant to chemical and biological threats. Optical pulse shaping and learning algorithms promise to further increase capabilities by optimizing the exact shape of a pulse to sense specific chemical species.

Extending ultrafast spectroscopy techniques into the ultraviolet (UV) and deep-ultraviolet (DUV) regions of the spectrum has proven to be a significant challenge. Achieving this goal is compelling for several reasons. First, the UV and DUV regions are the principle absorption bands for electronic transitions in most molecules. Second, the higher energy allows for much shorter pulses—as short at 25 attoseconds. The traditional approach for generating ultrashort deep-UV has been to use nonlinear crystals for harmonic generation. This approach is limited to the generation of narrow-band light at wavelengths longer than ~200 nm. Future research expects to develop tunable, shaped, broadband light spanning the visible and deep-UV regions of the spectrum, with sufficient pulse energy (~ microjoules) for applications of interest to the Army. Such a source, when coupled with advanced pulse shaping and learning algorithm technologies, would be of great interest for chemical and biological sensing, allowing new approaches to be developed that have potentially very high sensitivity. The ultimate goal of these experiments is to learn how to manipulate the electrons that control localized chemical bonds between two atoms in a molecule. Chemical physics will benefit tremendously from the ability to excite shaped “electronic wave packets” in deep-UV absorbing molecules. Excitation of electrons in this wavelength regime might be used to weaken some bonds while strengthening others, driving a systematic rearrangement of a molecule's structure. There are also other exciting theoretical applications of attosecond pulses that may be realized in part based on this research, including the tomography of molecular orbitals and the observation of molecular orbital dynamics during chemical reactions.

Dr. Chang’s group has succeeded in producing 120-attosecond pulses using a method called optical gating. In this technique, femtosecond pulses are focused onto a gas jet of sodium, or some other atoms, producing very high harmonics. Two beams of opposite circular polarizations are put together so that the field reaches a maximum at the instant the electric fields add (see Figure 13). This causes the electron in the atom to be ionized and then shoved back into the ion, causing the attosecond pulse. These techniques

promise to reach pulses as short as 25 attoseconds, a goal toward which Dr. Chang's group is progressing.

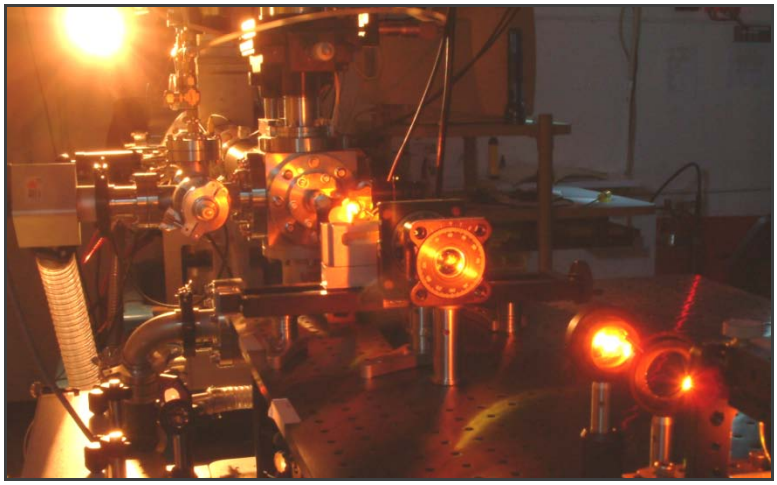

Figure **13.** Pulse laser equipment used by the Chang group to produce 120-attosecond pulses

Engineering Electron Orbitals - Andy Millis, Columbia University

The orbitals occupied by electrons in a crystal are determined by the specific atoms that comprise the crystal and the crystal's symmetry in its environment (pressure and temperature). Physicists wonder about the extent to which an experimenter can control the electron occupancy of one orbital or another. In complex oxides, electrons are easily localized into orbitals bound to a transition metal ion in the crystal. The physical properties of the material are determined by which orbitals are occupied and the degree to which they are occupied, the charge density, the energetic extent of the various orbitals, and the correlation strength (*i.e.*, how well electrons detect one another when travelling to the same ion in the crystal). The orbital occupancy is particularly intriguing as it relates to high-temperature superconductivity, spintronics, ferromagnetism, and perhaps other undiscovered phenomena. It was recently postulated that strain from nearby oxides can modify the orbital occupancy of another, and that superlattices (alternating layers of two materials) can accordingly force one material to behave unlike its bulk counterpart. See Figure 14 for an example of such a proposal.

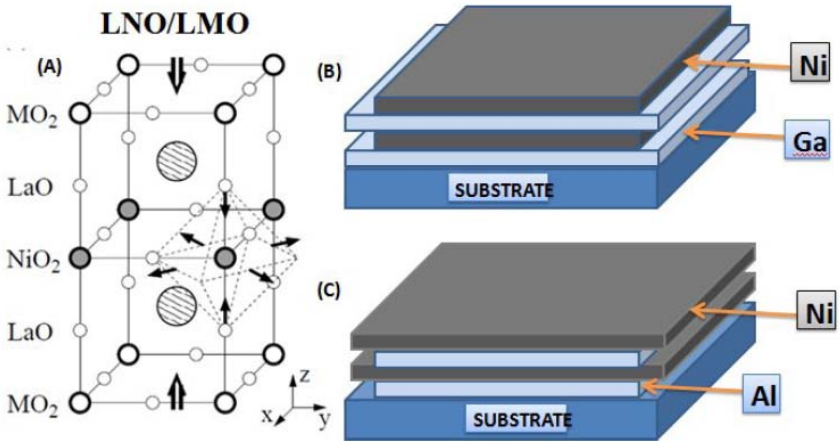

Figure 14. Illustration of stretching and squeezing of a $LaNiO_3$ layer: by forming a superlattice with other materials, ($LaAlO_3$ or $LaGaO_3$ proposed here) the preference electrons have for orbitals in-plane versus out-of-plane changes. If the balance can be tipped, a naturally non-superconducting nickelate should become a superconductor. *[Chaloupka, et al. 2008]*

This year, Dr. Andy Millis and his colleague Dr. Chris Marianetti, both theorists at Columbia University, have begun to address the matter of how much change can be induced in the orbital occupancy through the juxtaposition of different complex oxides. Initial studies by Drs. Millis and Marianetti have been conducted using a local density approximation to calculate the energy levels of the various orbitals in several complex oxides in a superlattice, with other oxides causing varying amounts of strain. They have also included a Hartree-Fock approximation to the on-site correlation energy mentioned above. Initial results are determining, theoretically, how strain and metal to oxygen bond lengths affect the energy separation between the pertinent transition metal d-state orbitals. In addition to the quantitative modeling, the approach provides insight into the mechanisms that drive orbital energies and occupancies.

These results are limited in their application due to two difficulties. First, the most interesting phenomena in these oxides are many-body effects, where small differences make huge impact on the material properties, whereas the approximations do not account for these effects. The important differences may be less than the accuracy of the approximation for a given computational capability. Second, the numerical approach only provides the ground state of the system. Experimental spectroscopies necessary to verify the accuracy of theoretical models can only observe excited states. Drs. Millis and Marianetti will soon employ a new computational approach termed dynamical mean field theory that provides two key advantages. First, it provides a more accurate calculation of the on-site correlation energy. Second, the theory includes a frequency term allowing excited states to be considered. As a result, spectra can be modeled that match the excited state(s) measured in the experimental studies of the materials. The approach is expected to provide a more realistic comparison between experimental and theoretical studies. If successful, the work will lay the foundation for providing experimentalists

with the conceptual tools necessary to “engineer” the occupancy of orbitals in complex oxides.

Fast, High Fidelity Quantum Dot Spin Initialization without a Strong Magnetic Field by Two-Photon Processes - Jelena Vuckovic, Stanford University

In this research project, the strong coupling regime of an Indium-Arsenide (InAs) quantum dot embedded in a Gallium-Arsenide (GaAs) photonic crystal circuit is explored with the goal of discovering new avenues and platforms for quantum information processing. Several major results have been achieved in this project, with two examples described in Section IV of the Chemical Sciences Chapter.

The first step in quantum information processing is the initialization of qubits to a known state with high fidelity. This is critical to data input and subsequent algorithm implementation. Previous work on this project has pointed to a fast and high fidelity spin initialization method for a negatively charged quantum dot coupled to a microcavity. The major advantage of the method is the absence of a strong magnetic field, because there is no need to mix the electron or the hole spin states. Instead, two-photon processes are employed to excite transitions that are otherwise spin forbidden by one-photon excitation (see Figure 15). A doubly resonant cavity is used to enhance both the excitation and the spontaneous emission rates. Modeling studies indicate that the method can achieve an initialization speed of 1.3 GHz and fidelity of 99.7% with realistic system parameters. An anticipated accomplishment for next year will be to perform high-fidelity and high-speed optical spin initialization experiments using the method proposed here. This will be an important demonstration leading to a practical quantum node, which does not require large superconducting magnets surrounding the cavity.

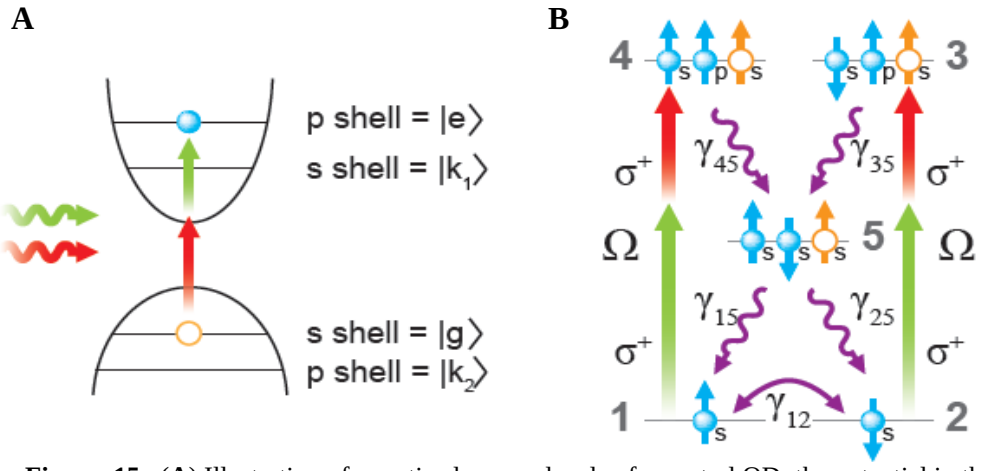

Figure 15. (**A**) Illustration of quantized energy levels of a neutral QD; the potential in the xy plane (perpendicular to the QD growth axis) is modeled as a two-dimensional harmonic oscillator. Upon two-photon absorption, an electron is excited from the valence band s orbital (|g>) to the conduction band p orbital (|e>). (**B**) Energy level diagram of relevant electron and trion states in a negatively charged QD. Electrons (holes) are shown in solid (open) circles. Subscripts indicate orbital labels. The ground levels are labeled 1 and 2. The first excited state is the trion state 5. The second excited states are trion states (charged electron hole pairs) excited by two-photon processes 3 and 4. The straight arrows indicate two-photon excitation, the curly arrows indicate various decays of excited states, and the curved arrow indicates spin flip.

I. PROGRAM OBJECTIVES

The ARO Chemical Sciences Program advances our knowledge and understanding of molecular science to develop future military technology. Chemistry overlaps and interfaces with other disciplines at ARO. The Chemical Sciences Division seeks to protect the Soldier with advanced materials, such as protection against ballistic, chemical and biological threats, and to enable the Soldier with advanced chemical processes, such as light-weight, small power sources and energetic materials. Many of these applications are years or decades in the future, but will not be possible without a firm foundation in basic research—promoted in part by the programs managed by the Chemical Sciences Division.

Programs in the Chemical Sciences interface with programs in the Life Sciences for the investigation of materials for use in chemical and biological defense and the discovery and design of biomimetic molecular structures. Interfaces between Chemistry and Materials Sciences can impact the creation of new materials through synthesis and processing, the evaluation of mechanical properties, and the study of materials at the molecular level. The Chemical Sciences programs also complement the research initiatives in the Physics and Electronics Divisions where research is aimed at understanding how chemical changes and chemical structures influence electrical, magnetic, and optical properties. Chemistry programs also overlap with research managed by the Environmental Sciences Division, in which new method and reactions are investigated for detecting, identifying, and neutralizing toxic materials. Programs in the Engineering Division also interface Chemical Sciences programs in their attempts to understand the processes of chemical combustion and power. Finally, the creation of new computational methods and models to better understand in molecular structures and chemical reactions bridge many of the research pursuits between the Mathematics and Chemical Sciences Divisions.

II. RESEARCH PROGRAM

A. General Information

The research awards managed by the Chemical Sciences Division include investigations categorized within four programs: polymer chemistry, electrochemistry and electrocatalysis, organic and inorganic chemistry, and physical and theoretical chemistry. These programs support work to advance our understanding of the basic principles underlying the macromolecular architecture and composition of materials as they relate to a variety of potential discoveries and applications. The basic research discoveries uncovered by these programs could provide new and enhanced chemical properties, small power sources, technologies for the detection and neutralization of hazardous chemicals and biological molecules, ignition, detonation, and sensitivity of energetic materials, and materials used in fuel cells, chemical sensors, and environmental cleanup. To maximize the impact of any discoveries, the Chemical Sciences Division coordinates research

thrusts and communicates frequently with Army scientists and engineers, the Office of Naval Research, and the Air Force Office of Scientific Research under Project Reliance.

B. Thrusts and Trends/Workpackages

The research awards managed by the ARO-LS Division can be grouped into four program areas or workpackages that describe the theme or thrust areas as identified within the existing ARO Broad Agency Announcement. Each of these four program areas address the strong potential for emerging fundamental knowledge in biotechnology to make rapid and highly innovative contributions in the areas of materials, sensors, systems and processes, including striking advances for human (*i.e.*, the Soldier), as well as engineered systems application. As goals are met and new requirements emerge, thrusts may be terminated with new ones initiated.

1. Polymer Chemistry - The goal of the Polymer Chemistry workpackage is to understand the molecular-level link between polymer architecture, functionality, composition, and macroscopic properties, such that new polymeric materials can be designed and synthesized to give the Soldier improved capabilities and capabilities not yet imagined. Towards this end, the program has two primary thrusts: Functionalized Morphology and New Synthetic Methodologies. Within these thrusts, high-risk, high pay-off research is supported to explore how changes in molecular structure and composition impact macroscopic properties, to design polymer molecular architecture, including the location of functional groups, such that it generates unique, well-defined morphologies, and to understand molecular-level, multicomponent transport in complex systems. In addition, research focuses on developing new synthetic approaches for preparing novel polymers with potentially interesting properties, the design of new polymerizable monomers, and the design and synthesis of polymers with targeted responses. While research focuses on high-risk, high pay-off concepts, long-term applications for the results include light-weight, flexible body armor, breathable toxic material protection for clothing, fuel cell membranes, and damage-sensing and self-healing materials for vehicles, aircraft, and other DoD materiel.

Current research projects in this program are exploring supramolecular building blocks to create new photohealable polymers that are stable at high temperatures and easy to process, are investigating the fundamental principles necessary to design molecules that exhibit targeted force activated molecular transformations and incorporate them into polymers and composites, and focus on the design of precision polymers to probe how precise acid group location affects the morphology and transport properties of polyolefins.

2. Electrochemistry and Electrocatalysis - The primary focus of this workpackage is to understand the basic science that controls reactant activation and electron transfer. These technologies provide the underpinning to enable future power generation in small electrochemically based power sources using a variety of fuels, including those from bio-sources. The topics of interest include investigating ionic conductivity in a variety of materials and understanding the chemical processes that allow multifunctional materials

to simultaneously provide ionic (either cationic or anionic) conductivity, mechanical strength, and suitable (generally very low) electronic conductivity over a considerable temperature range while exposed to aggressive chemical environments. This program includes studies that can lead to a detailed understanding of the function of electrocatalysts. In addition, reduction-oxidation (redox) materials that can function to store and release substantial concentrations of ions are pursued as part of this workpackage. These materials could be utilized in future battery concepts. Bio-fuels that can be tailored to replace currently available fossil based logistics fuels are also of interest. The program encompasses research projects that investigate the theoretical and experimental approaches to the above mentioned areas as well as development of analytical techniques/tools that allow researchers to measure fundamental properties and reaction rates of the materials of interest. Current projects include studies to characterize how length and density of polymer side chains affect the formation of water aggregates within the polymer (which in turn control the conductivity of polymer materials), studies of polymer electrolytes materials, studies of how the morphology of electrocatalysts affects the relative activity of the electrocatalysts, and a study of platinum/lanthanide based electrocatalysts.

3. Organic and Inorganic Chemistry . This workpackage focuses on developing a molecular level understanding of catalytic reactions, functionalized surfaces, and organized assemblies. This research will provide a foundational understanding for creating new materials and processes to protect the Soldier from hazardous chemicals and materials. More specifically, the program's goals include the design and synthesis of nano-structured catalysts with known properties and well defined morphologies, and to fully understand the kinetics and mechanisms of catalytic reactions. A mechanistic understanding of reactions on surfaces and interfaces as well as chemical interactions and transport on surfaces is also sought. Potential applications for this basic research include reactive materials for Soldier protection, advanced catalysts for hazardous materials degradation, and chemical sensors. An example of work in this area is the rational design of multi-functional nanomaterials which combines modeling and experimental work to design nanostructured materials with tailorable properties. The organized assemblies portion of the program is geared towards understanding how to control self-assemblies and how to exploit their dynamic behaviors. Specific objectives include the design of new synthetic approaches to self-assembled systems and incorporation of catalytically or biologically active species into these systems. The investigation of chemical systems that respond to external stimuli are also being investigated. Potential applications for basic research in this area include stimuli-responsive materials for Soldier protection, chemical sensing of hazardous materials, and stabilization and controlled release of reactive species for hazardous material destruction.

4. Physical and Theoretical Chemistry - The primary goals of this workpackage are to understand the molecular mechanisms of explosive detonation and propellant combustion, and to understand fundamental phenomena to enable selective and sensitive chemical sensing. It is expected that the knowledge gained in this research will serve as a basis for the design of the next generation explosives, propellants, and sensors. Current projects include the development of new coupled cluster ab initio methods to take

advantage of massively parallel computer architecture, a spectroscopic study of the relocalization dynamics in small combustion radicals, time-resolved spectroscopic studies of condensed-phase chemical reaction dynamics of energetic materials at high pressure (to 150 GPa) and temperature (to 4000 K), theoretical studies which enable the accurate prediction of molecular interactions in condensed phases, experimental and theoretical chemical kinetics measurements of unimolecular and bimolecular chemical reactions of energetic materials, and the development of new spectroscopic methods based on the principles of quantum control.

C. Research Investment

The total funds managed by the ARO Chemical Sciences Division for FY09 were $137.7 million, composed of the funding agencies described below.

The FY09 allotment for the ARO core chemistry (BH57-08) program was $5.3 million. The Department of Defense Multi-disciplinary University Research Initiative (MURI), Defense University Research Instrumentation Program (DURIP) and Defense Experimental Program to Stimulate Competitive Research (DEPSCOR) provided $6.2 million of funding to programs managed by the Chemical Sciences Division. The division also managed $37.1 million of Defense Threat Reduction Agency (DTRA) programs and $59.6 million of Defense Advanced Research Projects Agency (DARPA) programs, and $15.5 million provided by other DoD agencies. The Small Business Innovative Research (SBIR) and the Small Business Technology Transfer (STTR) programs provided $6.7 million for awards in FY09. Congressional Earmarks provided $6.3 million in research funds. Research funds in FY09 also included $1 million provided through other awards, including the Presidential Early Career Award for S&E's (PECASE) and the Historically Black Colleges and Universities (HBCU) outreach program.

D. Workshop and Symposia

1. Colloid and Surfactant Science Basic Research Workshop - Napa, CA, 10–12 March 2009. This basic research workshop brought together experts in academia, industry, and government laboratories to discuss new ideas and new needs in the fundamental research area of colloid and surfactant science. For many years, the ARO Organic and Inorganic Chemistry Program has invested in Surfactant and Colloid Science, however there has been very little change in focus within this program area. This workshop served as a forum to discuss recent advances in colloid and surfactant science, identify technical challenges, and develop a list of recommended areas for future investments that are new or not currently being developed.

2. Dynamics and Chemistry of Surfaces and Interfaces Basic Research Workshop - Savannah, GA, 23–25 June 2009. The goal of this workshop was to bring together experts in academia, industry, and government laboratories to discuss new ideas and new needs in the fundamental research area of surface science and interfaces. The fundamental interactions of toxic materials on catalysts or nano/microporous materials

are not well characterized and the interaction of large biomolecules on sensor surfaces is even less understood in many cases. This workshop provided an opportunity to discuss new advances in surface functionalization and characterization, modeling of mass transport on surfaces, and catalytic reactions on surfaces and at interfaces.

3. Chemical/Biological Filtration Strategies Working Group - Arlington, VA, 9–11 September 2009. This workshop brought together government and academic researchers who are experts in the fields of aerosol filtration, adsorption science, catalysis, materials science, reaction kinetics, reticular chemistry, and surface science to develop strategies for the synthesis, development, and design of novel porous compounds for next generation military filtration technologies. The workshop included presentations of the design rules and experimental evaluation techniques relevant to the filtration arena. Strategies to develop and optimize the performance of filtration systems against toxic industrial chemicals (TICs) were discussed.

4. Hazard Mitigation Technologies Workshop - Alexandria, VA, 21–23 October 2008. The purpose of this workshop was to introduce and obtain comment on the 2007 Chemical Decontaminant Performance Evaluation Testing Source Document (SD) and its biological decontaminant equivalent. The chemical testing portion of the workshop focused on the treatment of a panel of agents and the amount of agent remaining after treatment, a contact test to identify contact hazards, a vapor test to identify vapor hazards, and the supporting sample analyses. The biological testing portion of the workshop introduced the proposed biological efficacy procedures currently under development at Dugway Proving Ground, with support of Naval Surface Warfare Center Dahlgren Division and Edgewood Chemical Biological Center. During the workshop participant feedback was critical to ensure that all stakeholder perspectives were considered in producing the final version of the SD that supports test operations procedure development.

III. SPECIAL PROGRAMS

A. Multidisciplinary University Research Initiative (MURI) Program

The MURI program is a multi-agency DoD program that supports research teams whose efforts intersect more than one traditional science and engineering discipline. These awards constitute a significant part of the research programs managed by the Chemical Sciences Division. The unique aims of the MURI program were described in detail in Chapter 3, *PROGRAM IMPLEMENTATION*.

Advancing Polymer Science using Novel Biologically-active Polymers - The MURI "*Bio-Directed Hierarchical Assembly of Multifunctional Materials*" was awarded in 2004 to a team led by Dr. Thomas Russell at the University of Massachusetts, Amherst. These researchers are pursuing new avenues in polymer science by attempting to integrate biological components into polymers.

The simplest polymers consist of chains of repeating subunits (structural units) of the same type, while copolymers incorporate two or more types of subunits. The chemical properties of the subunits contribute to the global features of the polymer, such as strength and flexibility. The MURI team is designing novel copolymers that contain biologically-active proteins or compounds. These biologically-active components can include enzymes, antimicrobial compounds, antibodies, and/or enzyme inhibitors. While copolymers can be constructed to have a variety of features, the highly-specialized features of bio-molecules can confer unique opportunities in tailoring the morphology and functions of the copolymer. The MURI team aims to advance polymer science through the design, synthesis, and characterization of these novel multi-functional copolymers. These structures could potentially be used to develop antimicrobial coatings for fabrics or devices, sensor materials that detect and inactivate pathogens or toxins, and targeted drug-delivery molecules that encapsulate the drug and deliver high concentrations of a drug to specific locations in the body.

2. Testing New Types of Nanophotonic Materials for Controlling Light - The MURI "*Engineered Multifunctional Nanophotonic Materials for Ultrafast Optical Switching*" was awarded in 2006 to a team led by Dr. Eric Van Stryland at the University of Central Florida. This MURI aims to develop materials incorporating properties of high-speed nonlinear optics (NLO).

The field of NLO has enabled breakthrough developments in laser design, slowing light, and remote sensing. Linear optics describes a system that responds proportionally to the amount of light introduced (*e.g.*, add a lot of high-energy light, a lot of high-energy light is emitted). In contrast, NLO refers to systems that can absorb light (photons) and transfer the absorbed energy to another molecular system, providing a system that can be designed to amplify or absorb some of the energy and emit light of higher or lower energy, respectively. The goal of this MURI is to develop a new generation of materials that exhibit large NLO-absorption properties. These nanophotonic materials influence light at or below the nanometer wavelengths and have the potential to revolutionize the telecommunications industry by providing high-speed interference-free devices on a microchip. In addition, these materials could lead to improved visible-imaging applications (*e.g.*, microscopy), devices that will absorb high-energy light (*e.g.*, visors to protect the Soldier from sunlight and high-powered lasers without interfering with visibility at dawn or dusk).

3. Designing Revolutionary Polymers that Convert Damage into Useful Reactions - The MURI "*Mechanochemically-Active Polymer Composites*" was awarded in 2007 to design, synthesize, and characterize a revolutionary new type of polymers that contain mechanically-responsive components. This MURI team is led by Dr. Jeffrey Moore at the University of Illinois Urbana and is co-managed by the Chemical Sciences and Materials Sciences Divisions.

The use of polymers and polymer composites in construction materials, microelectronic components, adhesives, and coatings is well established. Polymer composites can form strong materials for use in civil and government engineering, such as siding materials or

armor. Unfortunately, these polymeric materials commonly crack when subjected to mechanical stress (damage). These cracks are a visible manifestation of the chemical changes (*e.g.*, breaking of bonds) that occur at the molecular level when the structure is damaged. Cracking can occur deep within the structure where detection is difficult and repair is almost impossible.

The investigators in this MURI team are designing, synthesizing, and characterizing revolutionary new mechanoresponsive molecules that respond to mechanical stress with pre-designed chemical reactions. These molecules, termed "mechanophores" may convert damage to useful chemical reactions. These useful reactions include changing color to identify the damaged regions or releasing catalysts that repair the damaged polymer. If successful, this research could be applied to construct polymer composites and mechanophores that alert the user to when and where a structure has sustained damage, then self-repair after damage, and then visually indicate that damage was repaired successfully. These self-repairing composites could be developed into a variety of self-repairing materials from parachute lines to armor.

4. Investigating Molecular Properties of Carbon Nanotubes - A new MURI was awarded in FY2009 to investigate the molecular properties required for preparing strong double-walled carbon nanotube (DWCNT) fibers. This MURI, titled "*Multiscale Design and Manufacturing of Hybrid DWCNT-Polymer Fibers,*" is led by Dr. Horacio Espinosa at Northwestern University.

The chief objectives of this research are to (i) develop a model system for predicting the molecular properties necessary for preparing new, high-strength fibers, and (ii) to prepare novel fibers composed of double-walled carbon nanotubes and polymers. The team will use multiscale computer simulations to bridge atomistic (electronic structure methods and reactive force fields), coarse-grain, and continuum scales to explore and understand DWCNT-polymer interactions, crosslinking effects (bond-breaking mechanisms), graphitization levels, and the impact of architecture on fiber strength, elasticity, and toughness. The investigators will use the results to predict fiber precursor properties necessary for optimum strength. The team will use predictive models to develop chemical vapor deposition techniques to produce highly aligned DWCNT mats with optimized density and surface chemistry. The mats will serve as precursors for fiber formation. Electrospinning will be used to produce fibers from DWCNT-aligned polymer matrices, which will enable control of nanofilament diameter and 3-D architecture. These materials will be characterized using *in situ* and *ex situ* microscopy (*i.e.*, assayed during and after reaction completion).

B. University Affiliated Research Center (UARC) - Institute for Soldier Nanotechnology (ISN)

The ISN, located at MIT, carries out fundamental, multidisciplinary nanoscience research relevant to the Soldier. Nanoscience research creates opportunities for new materials, properties, and phenomena as material properties (*e.g.*, color, strength, conductivity) become size dependent below a critical length scale of about 500 nanometers. This large

group of researchers includes 50 faculty across 10 departments at MIT. Research performed at the ISN falls into five Strategic Research Areas (SRAs). Each SRA is further divided into research themes. The five SRAs are summarized in the following paragraphs. Detailed descriptions of each SRA and its corresponding themes are available at the ISN program website (http://mit.edu/isn/research/index.html).

1. Light Weight, Multifunctional Nanostructured Fibers and Materials - This SRA is concerned with research to identify and apply diverse, nano-enabled functionalities to materials that can serve as building blocks for clothing and other gear to provide Soldier protection and survivability. Of particular interest are nano-scale coatings, core-shell and rod-rod nanostructures, carbon nanotubes, fibers, fabrics, layered and membrane structures. The research projects within this SRA are further divided among six themes.

i) Multifunctional fibers and fabrics
ii) Quantum dots for microfluidic fabrication, detection and sensing\
iii) Design and development of carbon-nanotube devices for imaging and sensing
iv) Muti-material, multi-functional fibers
v) Development of functional and responsive elastomers
vi) Nanostructured materials to control light and sound

2. Battle Suit Medicine - This SRA is concerned with research that can lead to improved medical and combat casualty care for the Soldier. Of particular interest are nano-enabled materials and devices applicable to far-forward medical treatment. In the nearer term these would find application in field hospitals and on the battlefield. In the longer term, technologies based on the basic research generated as part of this SRA would be incorporated in the multi-capability battlesuit. These technologies could be activated by qualified medical personnel (nearby or remotely located), by the Soldier in the field, and even autonomously with appropriate safeguards (*e.g.*, computer-controlled but with medic-override capabilities). Research examples include polymer actuators for imparting rigidity-on-demand (*e.g.*, for splinting wounds or preventing adverse movements after head or neck injury), materials and devices to enable controlled release of medications, methods for accelerated diagnostics of adverse medical conditions, and a MEMs-based device to prevent hemorrhagic shock. The research projects within this SRA are further divided among three themes.

i) Nanostructured actuators: first principles to fabrication
ii) Functional and responsive nanostructured surfaces
iii) Non-invasive medical monitoring and drug delivery

3. Blast and Ballistic Protection - This SRA will concentrate research on the critically important strategic Soldier capabilities of blast protection and ballistic protection. Recognizing the importance of blast related Soldier injuries in current operations, we are increasing the ISN's efforts in blast protection. This will complement and indeed enrich our ballistic protection research. In particular, this SRA will direct considerable assets towards understanding blast interactions with materials including human (brain) tissue as well as various anthropogenic energy absorbing structures including microframe

structures that contain nano-trusses. The research projects within this SRA are further divided among three themes.

- Lightweight nano-architectures for ultra-strong energy absorbing materials.
- Materials and Structures for blast Protection and injury mitigation
- Lightweight nanocrystalline alloy fibers for blast protection

4. Chem/Bio Detection and Protection - Research in this SRA will provide new scientific and engineering understanding to enable the detection of environmental hazardous substances as well as means to protect the Soldier from these substances. Research encompasses different means to obtain nano-scale polymeric coatings that provide specific protective functionalities, unique approaches to the sensing and characterization of various materials including toxic substances that exhibit identifiable chemical signatures, and development of the understanding needed to manufacture multi-layered 3D nano-structures from foldable 2D nano-patterned surfaces. The research projects within this SRA are further divided among three themes.

- Multifunctional and switchable surfaces for protection and survivability
- Ultrasensitive nanoengineered chemical detectors
- Nanostructured origami

5. Nanosystems Integration. This SRA is concerned with research to create or exploit nano-scale materials and devices and to understand their behavior within capability-enabling systems. Research will also seek the understand non-RF, fabric-enabled communications, including a laser-to-uniform communications system that works in free space. Research will also examine the use of nano-structured materials to enable observable optical nonlinear responses at very low power levels. The research projects within this SRA are further divided among four themes.

- Nanoelectronics
- Integrated fiber and fabric systems
- Non-RF fabric-enabled communications
- Enabling optical nonlinear capabilities for the soldier

C. Small Business Innovative Research (SBIR) Program—New Starts

The design of the SBIR program differs significantly from many other programs managed by ARO, as described in Chapter 3, *PROGRAM IMPLEMENTATION*.

1. Small Molecules for Neutralizing Chemical Agents. Three Phase I SBIRs were awarded to develop improved materials for detoxifying chemical warfare agents (CWAs) at ambient temperature using a catalytic reaction.

- *Hydrolysis of Chemical Warfare Agents Using an Organocatalyst*, awarded to TDA Research, Inc.
- *Carbosilane Organocatalysts for CWA Neutralization*, awarded to Seacoast Science, Inc.

Current methods for chemical decontamination are labor intensive, imposing a high logistical burden and make it difficult to maintain normal operations; however, catalytic reactions at ambient temperature can decontaminate classical CWAs. Unfortunately, current catalysts require metals in the active site, either in traditional metal/ligand structures or in enzymes. Recent research has shown that some metal-free, all-organic molecular assemblies produce very active catalysts. These SBIRs aim to develop one or more new non-metal-containing, low molecular weight organocatalysts that detoxify the classical CWAs at room temperature. The potential effects of a simulated CWA on the catalytic activity of the molecule will also be characterized. If successful, these catalysts will provide the Army with new methods neutralizing CWAs and protecting the Soldier.

2. Antimicrobial Coatings for Textiles - Two Phase II SBIRs were awarded to continue development of a thin-film coating that can provide long-term antimicrobial activity to textiles used in Soldier protection.

- *Antimicrobial Polymer Deposition Process for Enhanced Textile Adhesion*, awarded to Physical Optics Corp.
- *Thin Film Coatings for Antimicrobial Textiles*, awarded to Luna Innovations Inc.

While Phase I results demonstrated that a gas-phase deposition process was effective in applying antimicrobial coatings to certain fibers, the Phase II awards will advance these earlier discoveries by determining the optimal methods for each variable in this process. The optimization process will include investigations of the ideal coating composition, polymerization conditions, and the best fabric (*e.g.*, cotton, nylon) or fiber (*e.g.*, multi-filament, woven) to be used as targets for applying the antimicrobial coating. In addition, the antibacterial properties of the coated fibers will be fully characterized. If successful, these antimicrobial coatings can improve Soldier performance by preventing or reducing the colonization of microorganisms, some of which are associated with debilitating or life-threatening diseases.

3. Microencapsulated Chemiluminescent Tags for Tracking - A Phase II SBIR, *Improved Physical Security through Perimeter Tagging*, was awarded to Physical Sciences Inc. to develop an environmentally friendly, microencapsulated chemiluminescent formulation that can be designed to emit light at tunable wavelengths. The properties of two formulations that showed promise for tagging purposes in Phase I results will be studied in greater detail. Taggants are of interest for the tagging and tracking of Army materiel.

4. Anti-fog Coatings for Respiratory Devices - Three Phase I Chemical/Bio Defense (CBD) SBIRs were funded to design and develop a nanotechnology processing and fabrication technique to add anti-fog coatings on lenses of respiratory protection systems.

- *Anti-Fog Coating for Lenses*, awarded to Triton Systems, Inc.
- *Durable Anti-fog Coatings for Respiratory Protection Systems*, awarded to Luna Innovations, Inc.

- *Durable Anti-fog Coatings for Contoured Plastic Substrates Using Nanoparticles with Tunable Size and Surface Chemistry*, awarded to InnoSense, LLC

The anti-fog coatings currently available will degrade in performance as a result of cleaning and sanitization procedures. Recent research in nanotechnology processes has revealed a variety of techniques suitable for developing an innovative high performance anti-fog coating, such as the generation of superhydrophilic and superhydrophobic coatings. These SBIRs aim to demonstrate the feasibility of generating anti-fog coatings that are resistant to abrasion, and integrating these methods into a low cost and consistent process. The development of coated lenses or film inserts that exceed capabilities of current anti-fog coating technology and procedures will improve Soldier safety and effectiveness when respiratory devices are required.

5. Dry Adhesive to Enhance Sealing of Respiratory Masks - Three Phase I CBD SBIRs were funded to design and fabricate a dry adhesive to enhance the sealing performance of a full-facepiece respiratory protective mask.

- *Bio-Inspired Dry Fibrillar Adhesives for Enhanced Sealing of Respiratory Protective Masks*, awarded to Nanogriptech, LLC
- *Bio-Inspired Dry Adhesive*, awarded to Triton Systems Inc.
- *Bio-Inspired Dry Adhesives*, awarded to Technova Corp.

While man-made adhesives rely typically rely on chemical interactions, many biological species such as the gecko use elasticity, van der Waals forces, structural design, and possibly capillary forces to rapidly attach and detach from surfaces. These biological adaptations in combination with dry or oil-coated hairs, enable strong, repeatable attachment and detachment, and are self-cleaning against dirt and contaminants on surfaces. These SBIRs aim to develop a novel, bio-mimetic (imitating biological systems) adhesive to enhance the sealing of a respiratory protective mask. The adhesion, friction, and shear forces required for sealing a full-facepiece respirator to the face without a head harness will be identified. Based on these requirements, sample dry adhesives will be fabricated and tested on skin. A feasible adhesive in this application would ensure that the mask seal maintains good contact with the facial skin surface in the presence of sweat, oils, dirt, and facial hair, and ultimately benefit the Soldier by providing more reliable and flexible respiratory protective devices.

6. Sensor System for Detecting Chemical Agent Exposure - Two Phase I CBD SBIRs were funded to develop a near real-time sensor system capable of measuring the amount of a simulated chemical agent (methyl salicylate; MeS) present on the skin, beneath a protective garment.

- *Accurate Real-time Methyl Salicylate Sensing System*, awarded to Intelligent Automation, Inc.
- *A Quarter Sized Optical NEMS Based Methyl Salicylate Detector*, awarded to Imaginative Technologies, LLC

Recent advances in detection technologies and semiconductor development may allow the development of systems that can selectively detect chemical vapors in trace quantities. These SBIRs aim to develop a laboratory prototype of a MeS sensor system that provides near real-time detection of MeS infiltration through a protective garment. The prototype must be able to fit near a number of body regions and function accurately in the presence of human sweat, in varying temperatures, and in rapidly-fluctuating air flow. A MeS sensor system could provide data throughout the duration of a simulated chemical exposure or if simulated leaks should occur in protective clothing while worn by active military personnel. These data can be used to develop improved protection methods for Soldiers as well as predict the battlefield conditions where Soldiers may require greater protection.

7. Improved Virus Vaccine - A Phase II CBD SBIR, *Improved Venezuelan Equine Encephalitis Virus Vaccines*, was awarded to Physical Sciences Inc. to focus on the generation and comparison of the immunogenicity and efficacy of several alpha-Gal-modified Venezuelan Equine Encephalitis Virus **(**VEEV) vaccine candidates. Recent use of alpha-Gal-modified anti-cancer vaccines has revealed increased vaccine effectiveness as shown by preclinical and clinical results. This SBIR aims to generate alpha-Gal-modified VEEV vaccines, test the most potent candidates in a non-human primate model, and develop an assay validation to support large-scale vaccine manufacture. An improved VEEV vaccine will enhance antiviral vaccine development, vaccine potency, and vaccine immunogenicity which should lead to a reduction in the overall number of required vaccinations and a decrease of the vaccine dose. If successful, these applications will make vaccine production more cost-effective and more easily available, thereby providing protection to the Soldier.

IV. SCIENTIFIC ACCOMPLISHMENTS

Ion-Containing Nanostructured Polymers - Michal Hickner, Pennsylvania State University.

The goal of this research is to define the molecular parameters of ionic block copolymers related to selective transport and to develop structure-property relationships in order to provide a better understanding of the link between chemical composition, nanostructure, and transport. During the past year, novel copolymers for which only the middle block is susceptible to sulfonation, were synthesized using ATRP - poly(hexyl methacrylate)-b-polystyrene-b-poly(hexyl methacrylate) and poly(perfluorooctyl methacrylate)-b-polystyrene-b-poly(perfluorooctyl methacrylate). The middle block was successfully sulfonated in these copolymers. These polymers are of interest because the sulfonated middle block can be used to tune sulfonation level and therefore transport properties. The morphology of the polymers was characterized using small angle X ray scattering (SAXS) and transmission electron microscopy (TEM), and it was found that films with highly ordered morphologies have higher proton conductivity than those with disordered morphologies (see Figure 1).

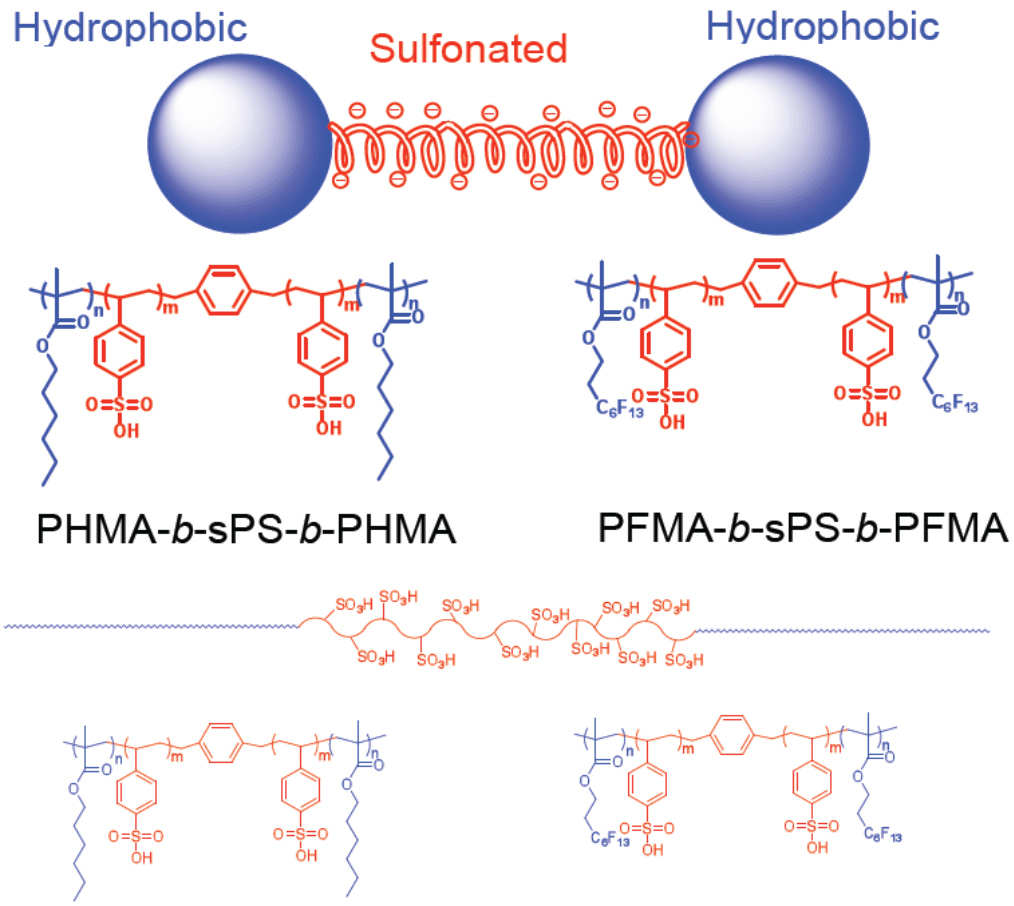

Figure 1. Midblock sulfonated triblock copolymers: researchers successfully integrated a sulfonated middle block in these polymers, surrounded by the hydrophobic (water-repelling) subunits on either side. These sulfonated middle blocks that can be used to tune the level of sulfonation in the entire polymer, thereby providing a method for modulating the transport of these polymers in a variety of solutions.

Flexible Hollow Fiber-based Lasers - ISN, MIT

The recent invention of flexible hollow fiber-based lasers has created a new tool to perform delicate medical procedures. The laser technology, developed by MIT Professor Yoel Fink at the Institute for Soldier Nanotechnologies (ISN), was initially used in the removal of a brain tumor in a 19 year old civilian, and has now been used in airway procedures as well as central nervous system (CNS) procedures, including intracranial and spine tumor and transnasal pituitary surgeries. Research investigation into making fiber-based devices was key to enabling this technology. Elements of this research have transitioned to an ISN 6.2 project to enhance FIDO® hand-held explosives detectors with multi-analyte capabilities. This research originated in 1993 as a DARPA-sponsored, ARL/ARO-managed project on omni-directional mirrors that later evolved into current research on hollow core fibers. Additional research involving these unique fibers involves optical line-of-sight, laser-to-uniform, free-space optical communications for identification, and sensors for far-forward medical triage. Incorporation of fibers into Soldier uniforms will enhance capabilities at significantly reduced weight.

Synthesis Nanoparticle-polymer Composites with Tailored Assembly - Todd Emrick and Alfred Crosby, University of Massachusetts, Amherst

This researched focused on understanding the effect of nanoparticles on the mechanical properties of polymers. Investigators could then use their understanding of these effects to design polymer composites containing nanoparticles that would confer unusual or enhanced properties to the entire composite, such as conductivity, sensing, and self-healing.

The investigators have successfully synthesized and characterized a series of nanoparticle-polymer hybrid materials that systematically vary the interfacial properties with the surrounding polymer matrix. These altered interfacial properties provide a method to overcome nanoparticle aggregation that previously prevented researchers from harnessing the optical and mechanical properties of these hybrid materials. Three different nanoparticle compositions were synthesized successfully. These nanoparticles were composed of either CdSe, Au, or silica/silsesquioxane cores (see Figure 2).

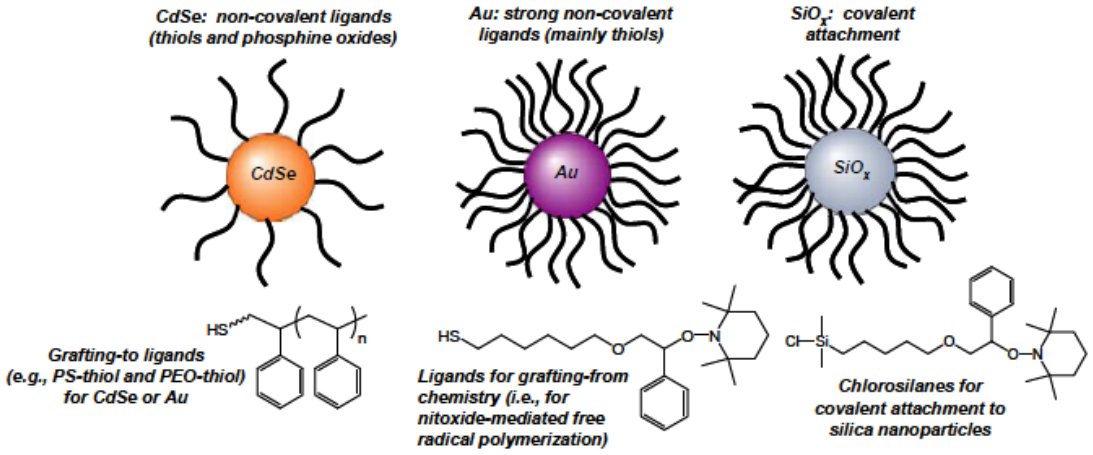

Figure 2. Schematic of tailored nanoparticles produced in the laboratory, containing CdSe, Au, or SiO_2 cores. These nanoparticles and the properties conferred by their unique cores are predicted to overcome nanoparticle aggregation that previously prevented researchers from harnessing the optical and mechanical properties of these hybrid materials.

These three nanoparticle compositions, composed of CdSe, Au, or silica/silsesquioxane, were chosen because each of these particle types would be compatible for integration with particular ligands (polymer subunits). As expected, the investigators have preliminary data demonstrating that these nanoparticles alter the characteristics of the polymer composite in which they are integrated, such as glass transition temperature of the polymer (the temperature at which the polymer forms glassy solid). These observations support the investigators initial predictions and will form a foundation for this research to continue in FY10.

Mechanoresponsive Polymers can Detect and May Repair Damage - Jeffrey Moore, University of Illinois Urbana

The MURI award "Mechanochemically-Active Polymer Composites," co-managed by the Chemical Sciences and Materials Sciences Divisions, led to two important results in 2009 in the burgeoning field of mechanochemical transduction. The concept of mechanochemical transduction is aimed at designing and constructing mechanoresponsive polymers—polymeric materials designed at the molecular level such that when a mechanical stress is applied, there is a molecular change resulting in the identification and repair of damage. The MURI team led by Dr. Jeffrey Moore demonstrated the concept for the first time in solid materials that polymers and polymer composites can (i) detect mechanical stress and (ii) can be designed at the molecular level to potentially self-repair after damage.

The use of polymers and polymer composites in construction materials, microelectronic components, adhesives, and coatings are well established. Polymer composites can form strong components for use in civil and government engineering, such as siding material to protect buildings and armor to protect the Soldier. Unfortunately, structural polymers are susceptible to damage, usually in the form of cracks. After mechanical stress, the default chemical response of these polymeric structures is the scission of covalent bonds, manifested as cracks within the polymer composite. Given that cracking can occur deep within the structure, this type of damage is difficult to detect and almost impossible to repair, which could render a damaged polymer unusable. This is the arena where discoveries in the field of mechanochemical transduction could meet significant needs that span multiple applications—from building materials to armor.

The mechanoresponsive solids designed by this research team contain specially-designed molecules called mechanophores. These mechanophores are the central component for transforming energy from mechanical stress into useful reactions. When pushed or pulled with a certain force, specific chemical reactions are triggered in the mechanophores. Although this research area is only in its infancy, these researchers have already constructed two important mechanophores: one that can detect damage and another designed to initiate structural repair.

A key component of self-regenerating material could be the capability to alert the user (e.g., the Soldier) to the damaged area, thereby cautioning the user against exposing that area to further stress until the damage is repaired. The "twisting spiropyran" mechanophore demonstrates this ability (see Figure 3). This mechanophore is incorporated within a polymer and responds to damage (e.g., extreme stretching) by displaying a visible color change. This color change is caused by the cleavage of a C–O bond within the spiropyran. This result provided the first demonstration of this concept in solids, including glasses, elastomers, and polymeric networks. Interestingly, the researchers found that this color change was reversible, as the mechanophore was restored to its original form after exposure to specific wavelengths of light. This mechanophore could be incorporated into a variety of materials used by the Soldier. For

example, parachute lines containing this mechanophore could produce an easily-identifiable color change when the lines have been stretched beyond safety requirements.

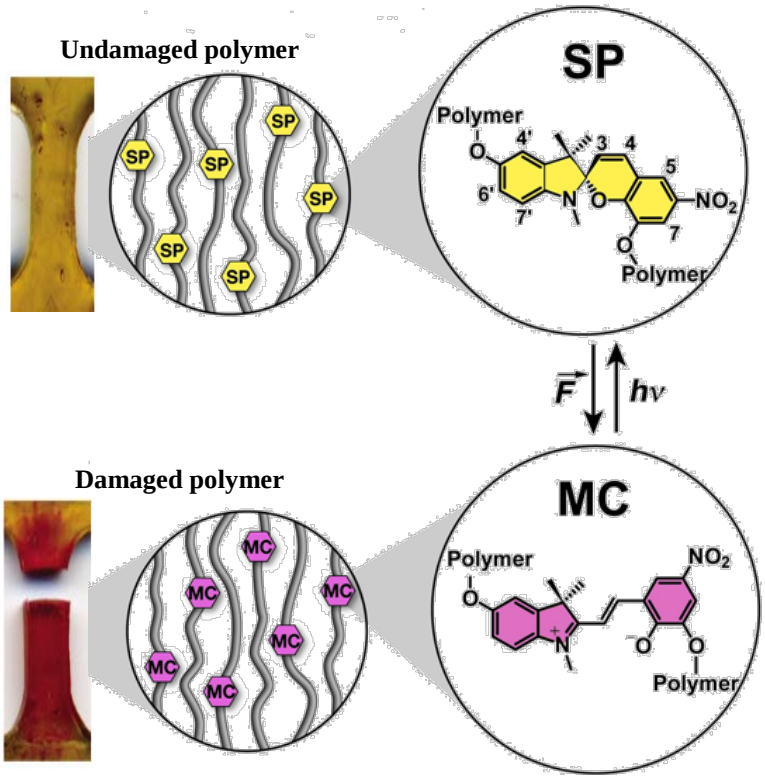

Figure 3. Twisting spiropyran mechanophores can detect damage: as the polymer is damaged (stretched), spiropyran molecules incorporated into the polymer composite change to a red color due to reversible C–O bond cleavage. In the photographs to the left, the red color increased in intensity until the polymer failed. *(Adapted from Davis et al., 2009)*

The masked cyanocacrylate was the second key mechanophore designed by these researchers in FY09 (see Figure 4). Although this particular mechanophore has not yet been tested, the researchers successfully designed and constructed a polymer with cyano-containing cyclobutane mechanophores incorporated into the structure. The masked cyanoacrylate mechanophore is designed to release cyanoacrylate-terminated polymers when mechanical stress is applied to the polymer backbone. In principle, this design will release cyanoacrylate molecules when the polymer backbone is damaged. Cyanoacrylate is probably best known as the active ingredient of the brand Super Glue®. The cyanoacrylate family of compounds rapidly polymerize after exposure to moisture in air, producing strong bonds that join surfaces together—often in less than a minute. After the MURI team has confirmed that cyanoacrylate molecules are released as predicted, this mechanophore could be incorporated into a variety of materials and the potential for self-repair can be explored further.

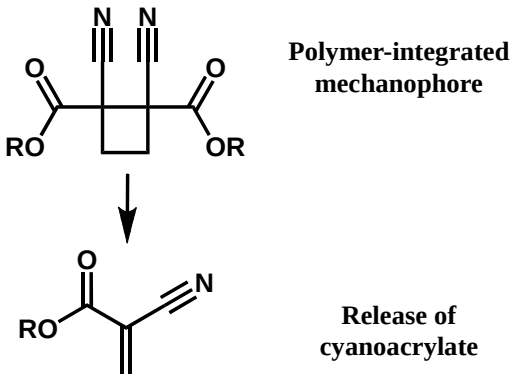

Figure 4. Masked Cyanoacrylate Mechanophores May Repair Damage: Cyano-containing cyclobutane mechanophores integrated into poly (methyl acrylate) backbone are designed to release cyanoacrylate, the active ingredient of Super Glue®, when the polymer backbone is damaged.

As reported in the news section of the May 7, 2009 edition of the journal *Nature*, the discoveries funded by this MURI "may become a milestone in polymer science, because the [researchers'] general design concept can probably be adapted to make a plethora of materials that translate mechanical stress into all kinds of useful chemical reactions." Most importantly for purposes of the Army, the latest results from this MURI could lead to future applications that benefit the Soldier, from parachute lines to armor. The two mechanophores designed by this research group could potentially be used to produce a self-repairing armor, where mechanophores in the polymer composite display the specific area(s) where damage was received (via a color change), repair the damage, and then return to the original color to show that damage was repaired.

Nanoporous Material May Allow Size-selective Filtration and Detection of Biomolecules - S. Weiss, Vanderbilt University

Research in the Weiss laboratory focuses on the design and synthesis of highly sensitive, reagentless nanoscale porous silicon waveguides for the capture and size-selective detection of biological molecules. Precise functionalization of inorganic materials for use in molecular recognition (*i.e.*, detection/sorting of specific molecules) is being studied. The researchers observed that the pore size, thickness, and refractive index of porous silicon can be readily modified by varying process parameters such as doping, etching time, and applied current density. Size-selective filtering capabilities of the porous silicon can be controlled by both nanopore diameters and functionalization. This concept was demonstrated with various sized DNA strands (8-24 bases). In order to increase detection sensitivity, the research team predicted that the probe molecule coverage can be enhanced by removing the polymer grating from the initial fabrication approach, resulting in an all-porous silicon grating coupled waveguide (see Figure 5). This new approach is based on the team's preliminary observations and will form a component of their research in 2010.

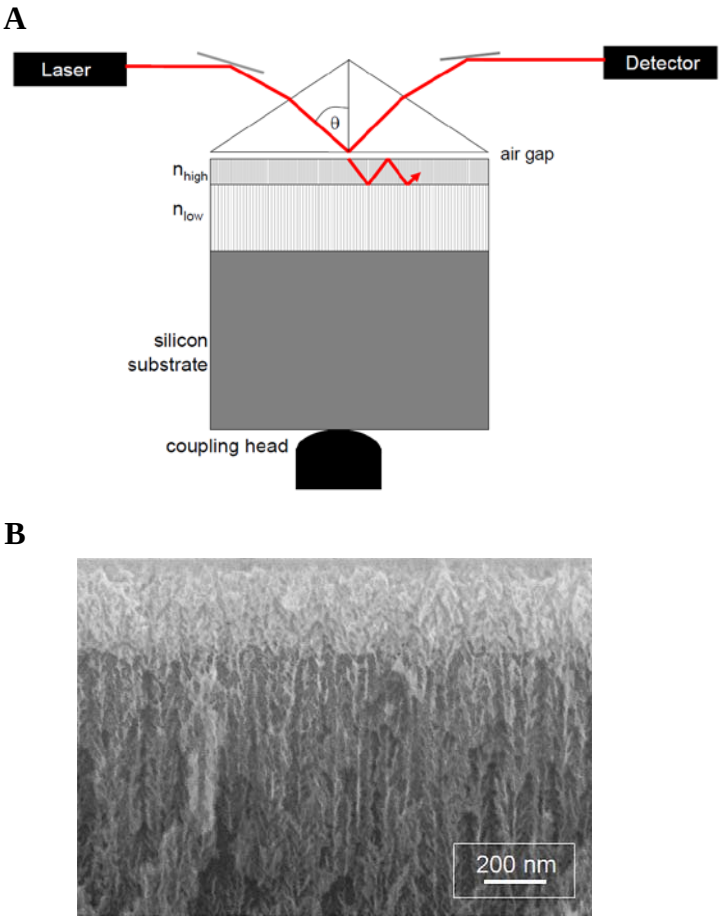

Figure 5. Design and characterization of all-porous silicon grating coupled waveguide: (**A**) the proposed porous silicon waveguide biosensor is illustrated, designed based on preliminary data characterizing the size-selective properties of the material. (**B**) The size-selective pores are visible in a scanning electron microscopy image of the porous silicon waveguide cross-section.

Adsorbate-Driven Anchoring Transitions in Liquid Crystals - N. Abbott, University of Wisconsin

The goal of this research is to provide an understanding of the orientational behavior of liquid crystals at chemically-modified surfaces—specifically how external stimuli can affect the orientational behavior of liquid crystals (LCs). The Abbott group has synthesized self-supporting gels by dispersing polystyrene colloidal particles in low molecular weight LCs in the isotropic state. Mechanically stable gels possessing micrometer-sized dynamic liquid domains separated by colloids are formed upon cooling to a particular temperature transition. The gels have been formed on metal ion functionalized surfaces, and tested with dimethyl methylphosphonate (DMMP). Exposure to the external stimulus triggers a change in LC orientation and optical properties (see Figure 6). The gels are continuing to be developed for specific and selective responses to a variety of stimuli. This new class of chemically responsive materials can provide a unique reagentless detection capability.

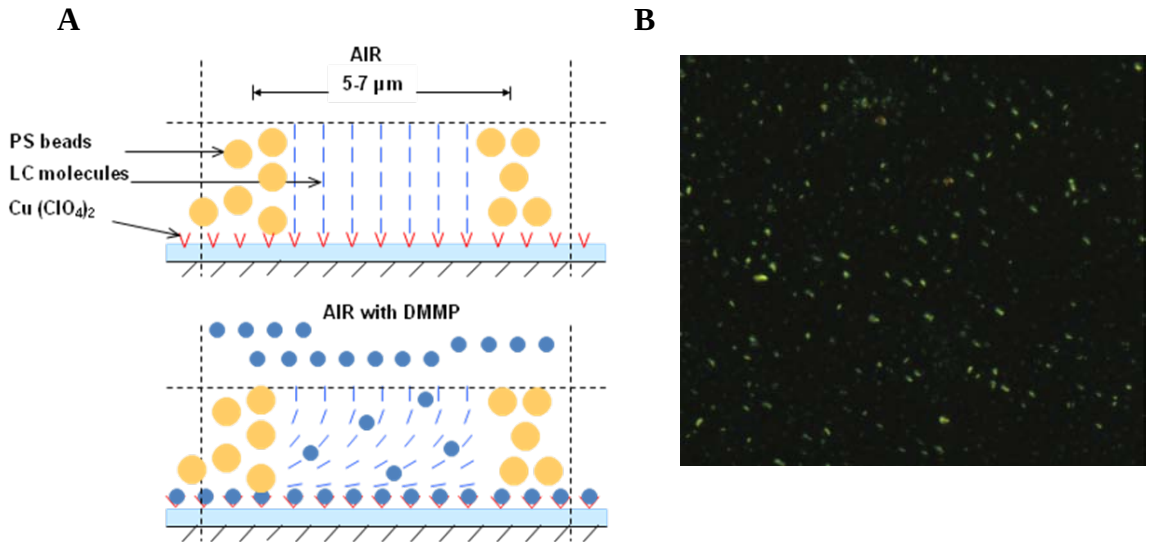

Figure 6. Results of LC gel exposed to DMMP: (**A**) the LC gel functionalized on $Cu(ClO_4)_2$ changes orientation in response to DMMP exposure. (**B**) A polarized light microscopy image of LC reveals changes upon exposure to DMMP (bright spots indicate change in LC orientation).

Structural Imaging of Microtubular Solid Oxide Fuel Cell Electrodes - Wilson Chiu, University of Connecticut

The detailed characterization of pore size, distribution, and connectivity is important to the understanding of transport in solid oxide ceramic materials. The ability to complete the characterization in a non-destructive manner allows a better selection of materials before extensive testing is carried out, and is a very useful tool for quality assurance. The work by the Chiu laboratory has extended the resolution for the characterization of pores in various solid oxides by more than an order of magnitude—from greater than one micrometer to sub-50 nanometers. The techniques developed can also characterize the associated electronically-conducting materials, such as Ni in a Ni-yittria stabilized zircornia (YSZ) cerment. A detailed understanding of the sample's microstructure allows the mass, electronic, and ionic transport in the pore, Ni, and YSZ phases to be accurately modeled with no empirical correction of the transport coefficients (see Figure 7).

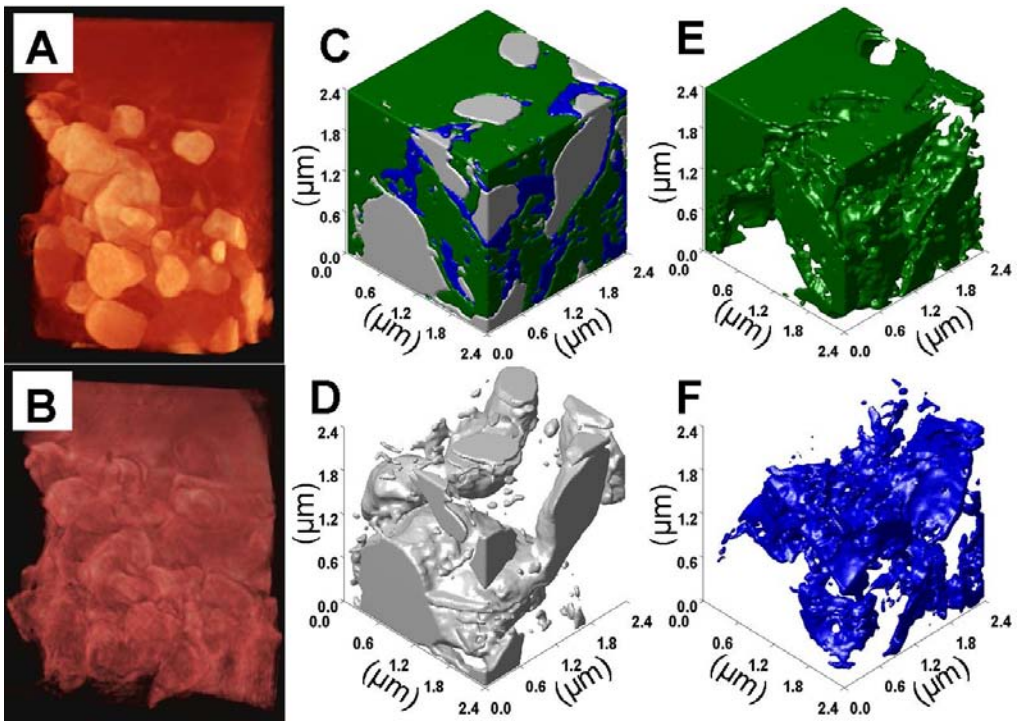

Figure 7. Characterization of porous Ni-YSZ cermet sample: X-ray micrographs of the porous Ni-YSZ cermet sample taken at (**A**) 20 eV above and (**B**) 20 eV below the Ni K-edge (8.339 keV) at 38 nm resolution (orange-Ni; red-YSZ; black-pore/empty space; scale bars indicate 1 μm). Reconstructions in 3D of the (**C**) full porous Ni-YSZ anode morphology, containing the YSZ (dark green), Ni (grey), and pore (blue) phases, (**D**) Ni morphology, (**E**) YSZ morphology, and (**F**) isolated pore morphology.

Modeling of Proton Transport, Water Distribution, and Methanol Permeability in Proton Exchange Membranes (PEMs) - Stephen Paddison, University of Tennessee

The dependence of proton conductivity on water content in polymer membranes is well known, but the details of understanding this process fall short of those required to straightforwardly chemically design an "ideal" membrane. This project has carried out dissipative particle dynamics (DPD) simulations in an attempt to better understand how molecular weight (MW) affects the hydrated morphology of the short-side-chain (SSC) perfluorosulfonic acid (PFSA) polymer. It demonstrated that such coarse-grained simulations are capable of revealing differences in the morphology of PFSA when either the length of the side chain or equivalent weight (EW) of the ionomer is changed. The project also carried out an investigation of the SSC ionomer modeled using macromolecules with EWs of 753, 798 and 849, each at three distinct MWs. The morphological structures were then investigated as a function of EW, MW and degree of hydration (with water contents corresponding to λ = 5, 7, 9, 11, and 16 H_2Os/SO_3H). Water contour plots reveal that the isolated water clusters present at lower water contents increase in size with increasing levels of hydration, and eventually form continuous water domains. The increase of MW induces strong aggregation of water clusters and results in larger, more elongated water domains, especially at high EW. Furthermore, the Bragg

spacing corresponding to periodicity of water domains, computed from radial distribution functions (RDFs), shows that the spacing between water domains increases with increasing hydration levels. This occurs especially for higher MW polymers at high hydration (16 H_2Os/SO_3H), whereas there is little difference at lower hydration levels between polymers with different MW.

Electronic State Specific Decomposition of Energetic Materials and Model Systems - E. Bernstein, Colorado State University

The goal of this research is to determine the molecular mechanisms and dynamics for the decomposition of energetic materials and model energetic materials as a function of their electronic and vibrational states. The experimental methods require the samples to be prepared in the gas phase by laser ablation and are cooled in a supersonic gas flow. The resulting beam of energetic molecules is placed in different vibrational and electronic excited states in order to determine their state-specific decomposition properties. The excitation is accomplished by nanosecond and femtosecond IR and UV laser pulses. Product molecules and radicals are detected as a function of pump pulse excitation energy and of the probe pulse timing with respect to the pump pulse. Detection of products is by fluorescence excitation, dispersion emission, and time-of-flight mass spectrometry.
The research team studied the decomposition of electronically-excited (226 nm photoexcitation) dimethylnitramine (DMNA), a model compound for (safer) study of the explosives RDX and HMX. The investigators found that a nitro-nitrite isomerization mechanism is the major channel of decomposition with a minor contribution from nitrous acid (HONO) elimination. These results provided researchers with a better understanding of the molecular mechanisms and dynamics for the decomposition of this reactant. The mechanisms for the decomposition of excited DMNA relative to the ground-state decomposition, are shown in Figure 8. The branching ratio between nitro-nitrate isomerization and HONO elimination channels is estimated to be 25:1.

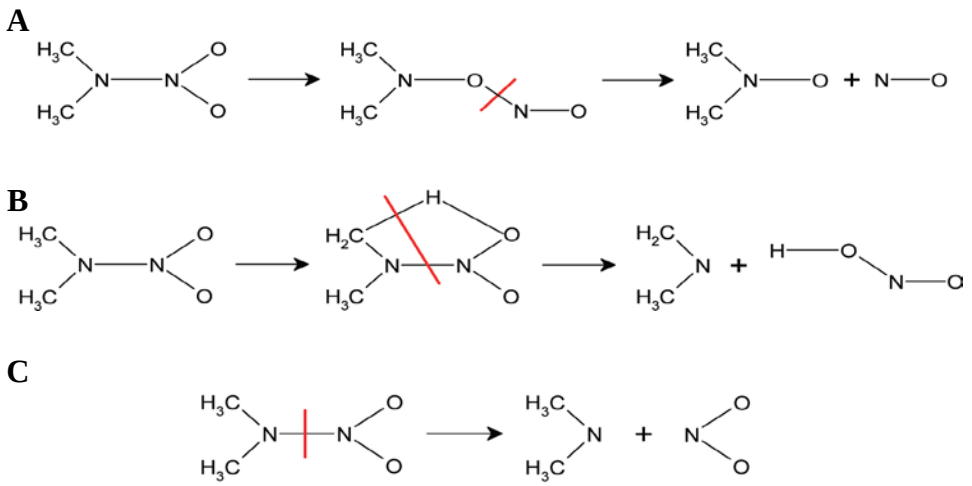

Figure 8. Mechanisms for DMNA: In the excited state, DMNA was found to decompose predominantly via the (**A**) nitro-nitrite mechanism and (**B**) HONO elimination, at a ratio of 25:1. In contrast, the major decomposition channel in the ground state is (**C**) by elimination of NO2. The characterization of these decomposition reactions provided researchers with a better understanding of the dynamics and decomposition of energetic materials, such as the explosives RDX and HMX.

Exploring the Scope of Controlling Quantum Phenomena - H. Rabitz, Princeton University

The research aims to bring advanced control concepts and algorithms into the ultrafast laser control laboratory (ULCL) at Princeton for implementation. The overall goal is to push the frontiers of quantum control science by establishing the principles, mechanisms and potential applications that may ensue from manipulating quantum phenomena. Operationally, this involves (i) the optimal shaping of ultrafast laser pulses which serve as "photonic reagents" for controlling quantum dynamics, and (ii) the subsequent probing of the resultant impact of the photonic reagent on the particular quantum system. As an illustration of the general capabilities of the UCLC at Princeton, The controlled manipulation of two flavin molecules, which are spectrally almost identical is illustrated in Figure 9. Despite the high degree of spectral similarity, dual operation with controls at 400 nm (shaped) and 800 nm through optimal control experiments produced dramatic degrees of distinguishing control between the two flavin molecules. The anticipated applications of this work include trace detection of analytes in the presence of interferences, such as sometimes occurs in environmental samples.

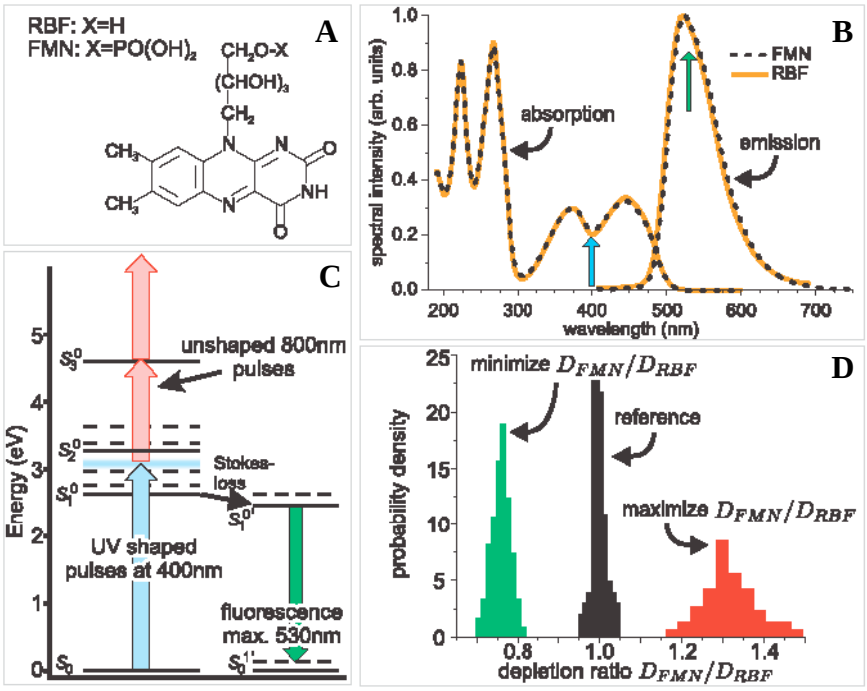

Figure 9. Modeling of structural similarities between riboflavin and flavin mononucleotide: RBF and FMN are quite similar (**A**) structurally and (**B**) spectroscopically, posing an extremely difficult task for their discrimination through selective excitation. Yet, operating with the principles and techniques of quantum control, using photonic reagents (*i.e.*, the shaped red and blue laser pulses in (**C**) produces dramatic levels of selective excitation as seen in (**D**) from the ratios of the signals. Note that the very significant separation between the red and green signals in D) under quantum control should be contrasted with the virtually identical spectra of these molecules in B).

V. TECHNOLOGY TRANSFER

Study of Morphological Precision in Free Acid Polymers and Ionomers - Ken Wagener, University of Florida

The goal of this research is to precisely control the chemical structure of acid containing polyolefins and to understand how molecular structure affects morphology. Discovering new methods to modify or control the morphology of polymers is an important component of basic research in polymer science that can ultimately lead to new uses of a polymer in the field. Monomers were designed and synthesized and sulfonic and phosphonic acid polymers were prepared. Protection/deprotection schemes were developed that enabled the precise placement of carboxylic acids on polymer chains. It was shown that the polymers had a new sheet morphology never seen before in these types of polymers. Samples were transitioned to the Army Research Laboratory and the University of Pennsylvania and x-ray scattering characterization was carried out.

Multiscale, Multiphysics Computational Approach to Dispersion and Properties of Polymer Nanocomposites - Venkat Ganesn, University of Texas

The focus of this research is to develop a more detailed fundamental understanding of polymer nanocomposites in order to improve properties and to add new capabilities without sacrificing inherent mechanical properties and processability. Modeling and simulation are used to explore how different design parameters control structure and morphology and ultimately bulk properties and behavior. The team is developing mesoscale models and simulations to explore how microscopic features, such as chemical functionality, molecular interactions, and external fields, relate to macroscopic structure and the dispersion of nanofillers in polymer matrices. Both the equilibrium and dynamic properties of polymer nanocomposites are being explored using atomistic simulations to probe the properties of polymer-filler systems and mesoscopic simulations and modeling to predict the equilibrium and nonequilibrium structural characteristics of nanocomposites. A new computer simulation module has been generated and transferred to the Army Research Laboratory where they are using it to predict the structure and rheology of biomimetic gels.

Incorporating Protein Nanotubes into Spun Materials with Potential Military Applications - J. Gerrard, University of Canterbury

The Gerrard group has demonstrated that protein nanotubes can be assembled from waste protein materials, and further functionalized to enhance the nanostructures' properties including strength, stability, and activity. Proof-of-concept experiments successfully incorporated glucose oxidase functionalized protein nanotubes into a polyvinyl alcohol (PVOH) film that demonstrated antibacterial action for several weeks (glucose oxidase was immobilized onto the nanoscaffold with glutaraldehyde). In order to address the uneven distribution of the protein nanotube components within the film, a project with Dr. Charlene Mello at the U.S. Army Natick Soldier Research, Development and Engineering Center (NSRDEC) has been established to investigate two different spinning technologies for incorporation of protein nanotubes into a matrix. These include electrospinning with the Nanospider™, and protein spinning which utilizes spider silk spinning techniques developed at NSRDEC. This technology transition will serve as a platform for adapting functionalized protein nanotubes into materials with military applications including coatings and composites, biosensors, drug delivery systems, nanowires, and bioremediation (see Figure 10).

Figure 10. Functionalized protein nanotubes: (**A**) 3D model of protein nanotube and (**B**) effect of film samples on E. coli growth (right)—PVOH film samples containing glucose oxidase and nanotubes are located at the top and bottom of the plate, and PVOH control samples are located on the left and right of each plate.

Kinetics and Mechanisms of the Destruction of Toxic Agents by Recyclable Catalytic Nanoparticles as Decontamination Media - T. Hatton, Massachusetts Institute of Technology

Novel, functionalized polymers capable of catalytically decomposing organophosphate compounds have been developed in Professor Hatton's laboratory. This fundamental catalysis work has led to a collaborative effort with the U.S. Army Natick Soldier Research, Development and Engineering Center for development of reactive barrier materials. Various elastomeric materials including butyl rubber, poly(vinyl alcohol), polyurethane, and Nafion ionomers are being chemically modified with oxime, amidoxime, and oximate groups, and demonstrate chemical decomposition of diisopropyl fluorophosphate while maintaining breathability and tactility. Dual chemical and biological protective fabrics are also being developed that utilize a microwave-assisted technique to incorporate both the oxime or amidoxime functionality and silver nanoparticles on the fabric surface.

Catalytic Decontamination: New Systems and Fundamental Studies - C. Hills, Emory University

A new class of large polyoxometalate (POM) catalysts that offer the dual capability of catalytic oxidation and quantitative acid/based sorption is being developed in the Hill laboratory (see Figure 11). POMs based on the {GeW9} unit are being evaluated for air-based oxidation of chemical simulants and ammonia uptake capacities, and will be transitioned to the filtration group at Edgewood Chemical and Biological Center (ECBC) for gas phase evaluations. This effort is an active partnership between the Hill group and ECBC as part of ECBC's overall effort towards development of the next generation military filtration technologies.

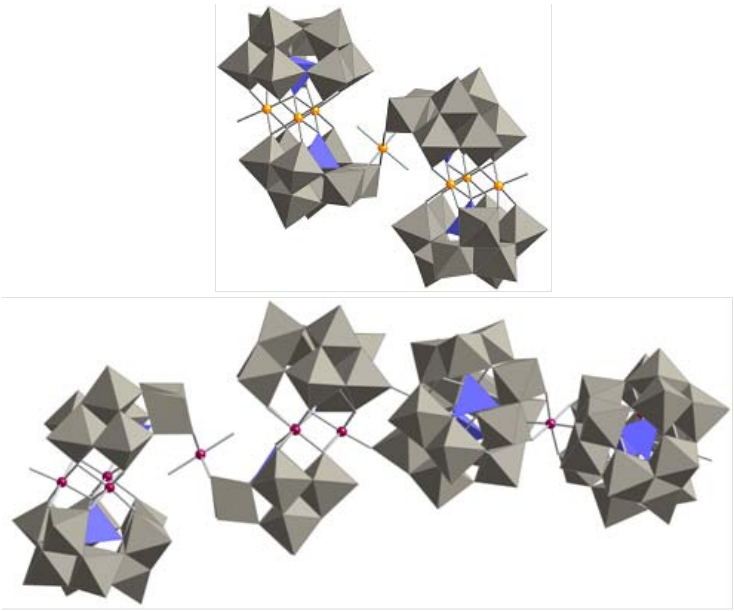

Figure 11. X-ray structures of two new structural classes of polyoxometalates (POMs): $K_{23}[\{(B\text{-}\bullet\text{-}GeW_9O_{34})(\bullet\ GeW_8O_{31})Mn_3(H_2O)\}_2Mn(H_2O)_2]$ (top; space group P-1; R1 = 6.31%); $K_{23}[\{(B\text{-}\bullet\text{-}GeW_9O_{34})(\bullet\text{-}GeW_8O_{31})Co_3(H_2O)\}_2Co(H_2O)_2]$ (bottom; space group $P2_1/c$; R1 = 14.4%).

Fuel Cell Power Systems for Unmanned Aerial Vehicles - Paul Osenar, Protonex, Inc.

Protonex is a leading fuel cell power system integrator that has been part of the ARO team since its inception via an ARO sponsored SBIR project in 2002. The company has traditionally developed low power systems for Army uses at (approximately) 500 W and lower, which is the power range for Soldier-portable generators. The company was recommended to the Naval research Laboratory (NRL) in 2004 as a possible supplier of fuel cell power systems for small unmanned aviation vehicles (UAVs). Subsequent efforts lead to world record endurance flights for electrically powered (quiet) UAVs, and the company has recently received an award from NRL to increase the power of their fuel cell power systems to 1.5 kW to support larger UAVs.

Symmetry Adapted Perturbation Theory - K. Szalewicz, University of Delaware

The Szalewicz group has developed a computer code which can efficiently and directly calculate intermolecular forces. It consists of a perturbation theory (PT) which is based on a density functional theory (DFT) description of isolated monomers but computes intermolecular forces using formulations beyond DFT. This method is called SAPT(DFT), where SA stands for the symmetry adaptation feature which properly accounts for the indistinguishability of electrons. Calculations for model compounds have shown that SAPT(DFT) reproduces all components of the intermolecular force, including dispersion, extremely well, in fact challenging the accuracy of WF-based methods. This code has been transferred to the Army Research Laboratory where it is currently being used to compute intermolecular forces of energetic materials.

ACES II *ab initio* Computer Code - R. Bartlett, University of Florida

Professor Rodney Bartlett has developed an *ab initio* code (*i.e.*, completely new) called ACES II, specializing in coupled-cluster (CC) type calculations of the electron correlation energy. The CC calculations are capable of predicting extremely accurate energies. This code runs in parallel and has been transferred to ARL's Weapons and Materials Research Directorate where it is being used by Army scientists on the HPC computer cluster.

VI. DIVISION STAFF

Dr. Douglas Kiserow, Division Chief
Program Manager, Polymer Chemistry

Dr. Robert Mantz
Program Manager, Electrochemistry and Electrocatalysis

Dr. Jennifer Becker
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Dr. James Parker
Program Manager, Physical and Theoretical Chemistry

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Contractor, Institute for Soldier Nanotechnologies, Institute for Collaborative Biotechnologies, Polymer Chemistry

Ms. Wendy Mills
Contract support for Organic and Inorganic Chemistry

I. PROGRAM OBJECTIVES

The principal objective of the Computing Sciences (CS) program is to provide increased performance and capability for processing signals and data, extract critical information and actionable intelligence to enhance the warfighters' situation awareness, decision making, command and control, and weapons systems performance. This program identifies and addresses the Army's critical basic research problems in CS where progress has been inhibited by a lack of novel concepts or fundamental knowledge. CS is pervasive in nearly all Army systems especially Command, Control, Communications, Computing, Intelligence, Surveillance, and Reconnaissance (C4ISR) systems. Research in this program has application to a wide variety of developmental efforts and contributes to the solution of technology-related problems throughout the Army's Future Force operational goals.

The Computing Sciences Division supports the following research areas:

- **Computational Architectures and Visualization** - is concerned with modeling, analysis, and design of both hardware and software architectures with special emphasis on the effect that the technological shift to heterogeneous, multi-core processors will have on these architectures. This subarea also involves innovative research in all aspects of visualization to include everything from computational geometry and computer graphics to large-scale computer simulations and virtual environments.

- **Information and Software Assurance** - addresses the research and development of highly assured, self-healing and survivable software and information systems that address the processing and delivery of authentic, accurate, secure, reliable, and timely information, regardless of threat conditions.

- **Information Processing and Fusion** – is focused on addressing research needs in converting sensor data into useful information to support effective decision-making. Topics supported under this program include image understanding, robotic perception, collaborative sensing by multimodality sensors, analysis and exploitation of high dimensional multimodality datasets, and brain-computer interfaces.

- **Numerical Analysis** – enables simulation as a third component of the scientific method, complementing theory and experiment. The program develops innovative, efficient, and accurate numerical methods and scalable scientific software methodologies, enabling mathematical models to be translated into high fidelity simulations

The major long-term objectives of the Computing Sciences Division are:

- Develop new mathematical theories, algorithms, and methods for sensing, perceiving, and understanding the environment in which the warfighter and their weapon systems operate. Advanced techniques in information and signal processing enable the establishment of full situation awareness and optimal decision making.

- Develop advanced computing, simulation and visualization as enabling tools that complement theory and experimentation for enhancing scientific discovery, engineering design and implementation, planning and training. This includes new effective architectures, domain-specific algorithms, implementation environments, evaluation of advanced computing systems, processing for large-scale simulation, graphic rendering, and visualization.

- Gain fundamental understandings in robust and resilient computing and establish new assurance theory, algorithms, methods, and tools that enable robust and resilient computing systems design and development for sustaining mission critical services and functions even with the presence of intrusions and compromises.

II. RESEARCH PROGRAM

A. General Information

The transformation of the Army to the Future Force will require investment in science and technology, especially computing and information science. The number of information sources on the battlefield will grow rapidly; computing and information science research must provide the technology to process this in real-time, and, to ensure that soldiers and commanders do not experience information overload that could adversely affect their ability to make decisions. Also, in spite of the increased complexity of future battlefield information systems, dependence on them will only increase; therefore these systems must be extremely reliable and secure. For this reason, computing science is a key technology underpinning the Future Force. The research topics described here are those needed to provide the Future Force the information processing, computing, security, and reliability needed to meet the challenges of tomorrow.

Each of the programs within the division balances between an opportunity-driven, high risk, high payoff scientific exploitation and needs-driven efforts that aim to solve the current needs of the warfighter. The division research investment strategy is coordinated with the relevant partner disciplines and computer scientists at ARO, ARL, other Army agencies, and related programs in other Department of Defense (DoD) and Federal agencies (ONR, AFOSR, DARPA, NSF, etc). The division's research portfolio is supported by the Army basics research core funding with substantial additional resources

from Director, Defense Research and Engineering (DDR&E) such as the Multidisciplinary University Research Initiative Program (MURI), and from other agencies, like DARPA, DHS, and NSA.

B. Thrusts and Trends/Workpackages

COMPUTATIONAL ARCHITECTURES AND VISUALIZATION

The two main thrusts of this program, as the title suggests, are computational architectures and visualization. Although each thrust has specific areas of interest, an overarching theme for both thrusts is the efficient managing and processing of massive data sets. This is due to the fact that the Army's ability to generate data of all types from the battlefield to the laboratory far outpaces the Army's ability to efficiently manage, process, and visualize such massive amounts of information. The computational architecture thrust attempts to address this issue by investigating innovative architectural designs of both hardware and software components and their interfaces. The visualization thrust addresses the issue by investigating innovative algorithms to render massive data sets and/or massive geometric models and to perform large scale simulations such as battlefield simulations, training simulations, and scientific simulations.

Computational Architectures – The goal is to develop new effective architectures, computational methods and software tools for future computing systems. As computer hardware continues to improve and change, architectural modeling and design concepts (or paradigms) as well as software must adjust to take advantage of these improvements. These new computational systems must be scalable (usable on large-scale complex problems and able to handle massive amounts of data) and accurate (precise enough to predict and detect phenomena of interest). Other important issues to be considered for these advanced architectures, especially with the shift of computer manufacturers to multi-core processors, are programmability, language and compiler support, real-time scheduling, resource-allocation and the development of a flexible software environment.

Visualization – The visualization thrust of this program is concerned with all aspects of visualization and computer simulation of interest to the Army and is not limited to any one type of data or computer model. Specific research areas of interest are, but not limited to, discrete mathematics, computational geometry, robust geometric computing, graph theory, geometric and solid modeling, interactive graphics, 3D visualization tools, and synthetic environments. Special emphasis is placed on making very large simulations and the visualization of massive data sets more computationally efficient and more interactive for the user.

INFORMATION AND SOFTWARE ASSURANCE

Information assurance for the individual soldier and for the systems that the Army must employ in the next few years is of paramount importance to the defense of this nation. Characteristics and concepts of operation of Future Systems, include lethality, survivability, mobility, agility, and sustainability. The need for authentic, accurate, secure, reliable and timely communication and information permeates these characteristics and concepts and is vital to the Army's success. The Future Force must have unprecedented situational awareness (including enemy and friendly awareness) at all times. It follows then, from the Army perspective, that Information Assurance must address the delivery of authentic, accurate, secure, reliable, timely information, regardless of threat conditions, over heterogeneous networks consisting of both tactical (mobile, wireless) and fixed (wired) communication infrastructures. As the Army places more reliance on winning the information war and providing the individual solder with highly automated and sophisticated tools, there must be an increased and improved awareness of the vulnerabilities that these systems possess. Ubiquitous, mobile, wireless, scalable, high-speed, and highly assured information processing systems will be placed in areas of usage never imagined in the past. Attacks on these systems will occur from hostile forces in both time of war and time of peace.

The ARO program in Information Assurance addresses five major problem areas:

- **Information Assurance for Mobile Wireless Communications**- The system needs to process information with integrity, confidentiality, and authenticity protection. In addition, survivability, self-healing, and energy efficiency are highly desired for these systems.
- **Assured Scalable Security Mechanisms for High Performance Computation and Networks** - Intrusion Detection, Fault Detection, Quality of Service, and Performance Monitoring
- **Cyber Situation Awareness Theory and Method**
- **Development of Resilient Technology for Mission Assurance**
- **Secure and Trustworthy Software Tactical Operations**

INFORMATION PROCESSING AND FUSION

Research is aimed at the development of theories, algorithms, and tools concerning data processing, information extraction, and information integration to support the development of real-time situational awareness and advanced targeting capabilities for military operations. Emphasis is placed on mathematical methodologies and algorithms for image processing, image understanding, video-based target recognition and tracking, and data/information fusion.

With the pervasive availability of unmanned systems in future military operations, advanced sensing will be of critical importance to the future force. This program emphasizes mathematical methodologies underlying automated sensing capabilities and

robust target tracking through innovative approaches such as bio-inspired geometric diffusion, video content indexing and retrieval, and optimized sensing asset allocation. Research efforts will support the creation of innovative algorithms for robust video-based tracking under challenging urban environments. Also supported is research on area monitoring using a network of cameras and other sensing modalities, potential applications including detection of improvised explosive devices (IEDs) and persistent surveillance. Research on brain-computer interfaces has the potential to provide a revolutionary capability for human-machine interactions. Work in this area actively supports advanced research in both minimally invasive and non-invasive imaging modalities for brain-computer interfaces.

The increased capability of electronic systems and proliferation of sensors are generating rapidly increasing quantities of data and information to the point that system operators and commanders are becoming saturated with information. An area of increasing importance is data and information fusion, especially from disparate sensors and contextual information. Sponsored research activities address several basic issues of data fusion, including information content characterization of sensor data and performance modeling. Of particular interest is research on collaborative target inference and target tracking by fusing data from disparate sensors as well as contextual information. Performance of target tracking can be drastically increased through integrated approaches that consider target recognition, data association, and motion estimation.

NUMERICAL ANALYSIS

The Numerical Analysis Program supports the strategic themes of the Computing Sciences Division by developing innovative, efficient, and accurate numerical methods and scalable scientific software tools. Such methods and tools assure that mathematical models can be translated into realistic simulations. The quantitative predictions of many modern theories can only be derived from extensive computations. As Army problems become more complex, new and better approaches are needed to understand and develop their solutions. The overall focus of the Numerical Analysis Program is on developing algorithms, which are needed to model new applications and discover general solution methods for large classes of problems.

Numerical computation and simulation have become an essential part of scientific investigation and engineering design. In science, it has become an accepted third component of the scientific method, complementing theory and experiment. In engineering, it is possible to simulate potential designs and analyze failures after they have occurred. Such simulations often require considerable effort to set up, considerable computer time on large scale parallel systems, and considerable effort to distill useful information from the massive data sets. In addition, it is often not possible to quantify how well the models simulate complex problems or the fidelity of resulting simulations. This problem is especially acute for simulations of failure processes. Data has become ubiquitous, but mathematically sound methods for incorporating these into simulations are incomplete. Finally, simulations are not fully integrated into operational decision

processes. Research to improve validation, relevance and completeness in modeling are critical. The emphasis in the Numerical Analysis Program is on mathematical research directed towards overcoming these and related shortcomings.

C. RESEARCH INVESTMENT

The **Computational Architectures and Visualization** work package funded a total investment of $3.2M with $800K in core funding to support 9 core programs, 3 Defense University Research Instrumentation Programs (DURIP), 3 Defense Advanced Research Projects Agency (DARPA) projects, 1 Small Business Technology Transfer (STTR) Phase 2 program, 1 Short Term Innovative Research (STIR) project, 1 Defense Experimental Program to Stimulate Competitive Research (DEPSCoR), 1 workshop, 1 Historically Black College and University/Minority Institution (HBCU/MI) project, and 1 Tribal College and University program. A number of core and other program projects received no FY2009 funds, but were active. University performers active in this work package include Louisiana State University, University of North Carolina, Southern Polytechnic State University, Southern Illinois University-Carbondale, Missouri University of Science and Technology, Arizona State University, North Carolina State University, University of Utah, North Carolina Central University, Miami University, Southwestern Indian Polytechnic Institute, Duke University, California State University - Los Angeles, and Carnegie Mellon University among others.

Approximately $10.1M was invested in the **Information and Software Assurance** work package with core program funding contributing a total of $850K. Included in the work package were 8 core programs, 6 workshops, 3 STTR Phase 2 projects, 3 Multi-disciplinary Research Initiative (MURI) programs, 2 DURIP projects, 2 STIR projects, 1 HBCU/MI program, and 1 Presidential Early Career Award for Scientists and Engineers (PECASE). The MURI topics supported under this work package are “A Cyber Awareness Framework for Attack Analysis, Prediction, and Visualization”, “Computer-aided Human Centric Cyber Situation Awareness” and “Designing Reliable and Secure Tactical MANETs”. A number of core and other program projects received no FY2009 funds, but were active. University performers active in this work package include George Mason University, Duke, Boston University, University of California – Davis, Michigan State University, University if Connecticut, Iowa State University of Science and Technology, Naval Postgraduate School, Carnegie Mellon, Penn State, University of Minnesota – Minneapolis, University of Wisconsin – Madison, and University of Texas – San Antonio among others.

The **Information Processing and Fusion** work package invested approximately $6.3M from all sources for FY09. Core program investment was $1,963K for support of 17 research projects and 2 workshops. Also included in the work package are 4 DURIP projects, 1 DEPSCoR, 2 projects funded under the Tribal Colleges and Universities program, and 4 MURI projects under the titles of “Engineering of Sensor Network Structure for Dependable Fusion”, “A Brain-Based Communication and Orientation System”, “Silent spatialized communication among dispersed forces”, and “Opportunistic Sensing for Object and Activity Recognition from Multi-Modal, Multi-Platform Data”.

Investments also include 2 STTR Phase I projects, 1 STTR Phase II project, and 2 SBIR Phase II projects. A number of core and other program projects received no FY2009 funds, but were active. University performers active in this work package include Rice University, Penn State University, Duke University, University of Connecticut, Michigan University, University of Florida, Albany Medical College, and University of Minnesota among others.

Approximately $879K of core funding was invested in the **Numerical Analysis** work package for FY09. The program increased from $629K with 9 active projects in FY08 to $879K and 15 active projects. The program also served as the initial launch agent for a new program in Biomathematics, resulting in 3 inaugural awards. Net result for the program was a 32% increase in funding and a 113% increase in activity (including the temporary stewardship of our Biomathematical efforts).University performers supported in the Numerical Analysis research program include the RPI, Clemson, NC State, UNC Charlotte, Washington State, Brown, Stony Brook, William and Mary, Rice, SMU, MIT, and University of Kansas.

D. WORKSHOPS

3-4 March, 2009 “ARO Special Workshop on Cyber Situation Awareness”, George Mason University, Fairfax, VA

11-12 May, 2009, “ARO Workshop on Distributed Camera Networks: Research Challenges and Future Directions”, University of California, Riverside, CA

20-21 July, 2009, “ARO Workshop on Trustworthy Social Computing”, University of California, Davis, CA

13-14 August, 2009 “ARO Special Workshop on Hardware Oriented Security and Trust”, University of Connecticut, Storrs, CT

21-22 August, 2009, "ARO Workshop on Machine Translation of Low Density Languages", US Military Academy, West Point, NY

25-26 August, 2009 “ARO Special Workshop on Trusted Cyber Physical System”, University of Connecticut, Storrs, CT

10-11 September, 2009 "ARO Special Workshop on Digital Forensics", Washington, D.C.

21-22 October, 2009, “Challenges in Information Evaluation and Extraction in Distributed Sensing Systems”, MIT, Cambridge, MA

III. SPECIAL PROGRAMS

A. DOD UNIVERSITY RESEARCH INITIATIVE (URI)

A MURI project entitled **Engineering of Sensor Network Structure for Dependable Fusion** was awarded in June 2007 to a team lead by Professor Shahi Phoha, Pennsylvania State University. Team members also include researchers from Harvard University, Duke University, and Ohio State University. The major objective of this MURI is to develop theoretical foundations and validation to address: (1) proliferation of multi-source sensor data due to DoD's tactical shift to network-centric warfare, (2) urban area monitoring demands of the Global War on Terror, and (3) collaboration needs of Future Combat System platforms. The emphasis is on network science & engineering, which enable construction of sensor networks to support dependable information fusion. This research effort is based on fundamental concepts of space-time neighborhoods in the vicinity of events, symbolization, nonlinear filtering & computational geometry to formulate rigorous mathematical methods and algorithms to capture the causal dynamics of distributed information fusion processes in Urban Sensor Networks.

A MURI project entitled **Opportunistic Sensing for Object and Activity Recognition from Multi-Modal, Multi-Platform Data** was awarded in August 2009 to a team lead by Professor Richard Baraniuk, Rice University. Team members also include researchers from Rice University, University of Maryland, University of Illinois, Yale University, Duke University, and University of California at Los Angeles. The major objective of this MURI is to develop a principled theory of opportunistic sensing that provides predictable, optimal performance for a range of different sensing problems through the effective utilization of the available network of resources. There are four thrusts of research: (1) scalable sensor data representations based on sparsity and lowdimensional manifolds that support dimensionality reduction through compressive sensing; (2) scalable data processing for fusing image data from multiple sensors of potentially different modalities for activity detection, classification, and learning; (3) opportunistic optimization, feedback, and navigation schemes for multiple mobile sensor platforms that adaptively acquire data from new perspectives to continuously improve sensing performance; and (4) experimental validation on real-world multi-camera video, infrared, acoustic, seismic, and human language inputs.

Two MURI projects on **Robust and Resilient Tactical MANETS** were awarded in 2008 to University of Maryland team led by Professor Vigil Gligor and to UC Davis team led by Professor Prasant Mohapatra. The goal of these MURIs is to use insights from multiple disciplines in networking, engineering, mathematics, and systems theory to develop the analytical models, tools, and mathematical representations for assessing, prescribing, analyzing, and predicting the behavior of robust and resilient mobile ad hoc networks under a total threat spectrum, and to provide security, robustness and resilience for tactical MANETs. The research teams will investigate: (1) mathematical representations and tools for modeling and analysis of resilient and robust MANETs, (2) theories that explain the MANET layered architecture and cross layer interaction (both intentional and unintentional), (3) theories that elucidate the relationships and

understanding of the trade-offs between fragility and robustnessl, (4) interaction of networks, particularly, MANETs, low energy wireless sensor networks, and wired communications networks, and (5) design of MANET survivability algorithms and architecture, resilient management mechanisms, threat spectrum analysis for information applications on MANETs, fault tolerant and attack resilient communication protocols, survivability requirements engineering, and security and trustworthiness in MANETs. The University of Maryland team's approach is based on the fundamental principles of active protocol monitoring for performance, stability and adversary handling, of employing communication channel diversity for robust end-to-end operation in the face of failures and deliberate attacks, and of exploiting cross-layer interaction for predicting the effects of performance changes caused by layer-specific failures and attacks on end-to-end MANET operation. Design and analysis techniques found in network theory, statistics, game theory, cryptography, economics and sociology, and system theory are used to develop, design and analyze models, tools, and mathematical representations for predicting performance and prescribing resilient, secure MANETs. The UC Davis team is developing a cross layer architecture that provides comprehensive security and resilience. Depending on the services desired, the new architecture will be able to adaptively provide the right trade-offs between performance, security and fault-resilience. The team currently undertakes three parallel but inter-coupled tasks geared towards: (1) performing measurements via real deployments and enhancing understanding of layer dependencies and vulnerabilities in mobile ad hoc networks, (2) building analytical models to characterize the behavioral nuances of these networks, and (3) design of new cross layer protocols that protect against vulnerabilities and provide the desired robustness.

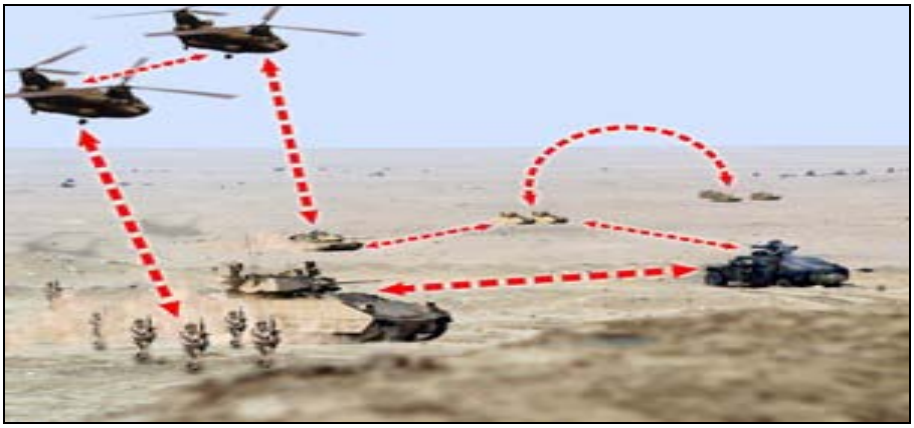


Figure 1. Mobile Ad Hoc Network (MANET).

Two MURI projects on brain network analysis and modeling for communication and orientation were started in August 2008 in collaboration with the Life Sciences Division. One project entitled **A Brain-Based Communication and Orientation System** is led by Dr. Gerwin Schalk, Albany Medical College, with team memebrs also from Washington University and New York University. The other project entitled **Silent Spatialized Communication Among Dispersed Forces** is lead by Professor Thomas D'Zmura, UC-

Irvine, with team members also from Carnegie Mellon University and University of Maryland. The objective of these MURIs is to develop the fundamental research needed to design a system for verbal communication and monitoring of attentional orientation that uses brain signals to provide, in real time, an accurate assessment of the user's intentional focus, eye movements, and imagined speech. The effort is focused on the following thrust areas: (1) the development of a synthetic telepathy system that uses automatic speech classification and recognition methods to decode electroencephalographic (EEG) recordings of brain cortical activity during covert speech; (2) communication of such covertly-spoken thought using an augmented-reality audio system with a spatialized speech channel; and (3) exploitation of electrocorticograms in epilepsy patients for interface design using invasive recordings and to develop algorithms needed to perform the task via non-invasive EEG only.

Complete situation awareness leads to effective defense and response to cyber attacks, especially those launched by adversaries with a state sponsorship. The ability to extract critical information and build intelligence leads to a better capability in attack prevention, detection and response, and in sustaining critical functions and services. Two MURI projects on **Cyber Situation Awareness** were awarded in 2009 to University of California, Santa Barbara, team led by Professor Richard Kemmerer, and to the Pennsylvania State University team led by Professor Peng Liu. The goal of this MURI is to explore and investigate cyber situation awareness theories and framework that support effective defense against cyber attacks, and to develop new algorithms and systems that can assist human analysts' cognitive situation awareness processes and decision making. The team will focus their research in the following key areas: (1) situation (knowledge and semantics) representation and modeling that support multi-level abstraction and transformation of data to intelligence, (2) information fusion that can effectively combine raw and abstracted intelligence of different confidence levels to support optimal response, (3) uncertainty management and risk mitigation through probabilistic hypotheses/reasoning and sensitivity control and using multi-level statistical analysis to manage incomplete and imperfect situation information, (4) leveraging cognitive science understandings to automate human analysts' cognitive situation-awareness processes (to recognize and learn about evolving situations, to create automated hypothesis generation, and to reason in both pre-attack planning and post-attack response), (5) a new framework unifying perception, comprehension, and projection functions and integrating situation recognition, impact assessment, trend analysis, causality analysis, and situation response together, (6) establish advanced mathematic models for quantitative analysis and assessment of system assurance, and (7) rapid repair, recovery and regeneration of critical services and functions as part of automatics response to attacks.

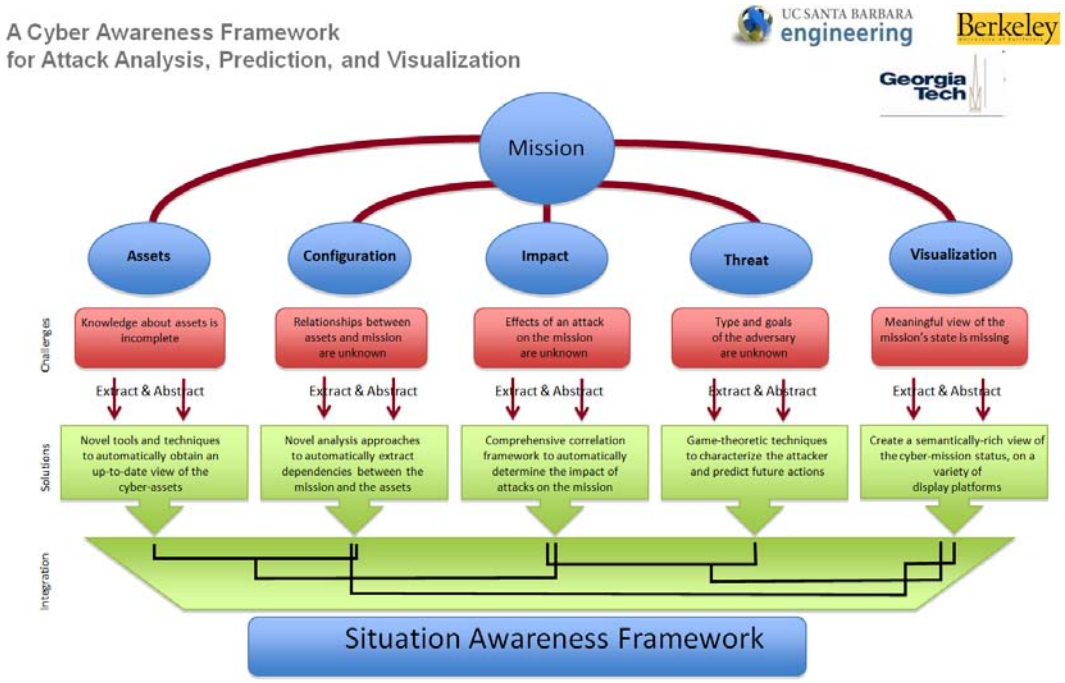


Figure 2. Cyber Situation Awareness Framework.

B. University Research Centers

CyLab of Carnegie Mellon University - CMU CyLab combines the efforts of more than 40 researchers and 100 students from the College of Engineering, the School of Computer Science, H. John Heinz III School of Public Policy, and the CERT Coordination Center. In the area of information assurance, current research is carried out under six themes:

- Resilient and self-healing systems
- User authentication and access control
- Software measurement and assurance
- Information privacy
- Threat prediction modeling
- Business and economics of information security

CMU Cylab is working closely with Army Research Laboratory on breakthrough technologies to secure and protect the computing and communication capability of U.S. Army. Successful results from the funded research will contribute to the development of a highly assured, efficient, and survivable information system for future combat forces.

Cyber-Threat Analytics (Cyber-TA) Research Consortium - The mission of the consortium is to research and develop advanced capabilities to defend against large-scale network threats and create new technologies to enable next-generation privacy-preserving digital threat analysis centers. Currently, the consortium is led by SRI International, a

non-profit research institute. The consortium consists of 9 universities, 2 non-profit research organizations, and 3 small businesses, with more than 20 researchers participating. The main primary project thrusts are:

- Privacy preserving schemes for Internet-scale collaborative sharing of sensitive information and security log content
- Real-time *Malware*-focused alert correlation analyses, including contributor-side correlation applications with repository-side reassembly
- New threat-warning dissemination schemes to rapidly inform large-scale multi-enterprise environments of new attack patterns and malware mitigation strategies that take advantage of the collaborative data correlation analysis

The consortium of researchers has developed cutting edge technologies and new tools that have been deployed to protect DoD's information infra-structure. Most recently they have developed effective analysis tools and counter-measures against the latest wave of intelligent exploits such as the Conficker attacks.

Secure Open Source Institute (SOSI) - a national center that researches and develops trustworthy open source systems, techniques, and tools was established at North Carolina State University in summer of 2008. The research team aims at developing a new computing architecture called a Secure Virtual Computing Architecture (SVCA) that will provide an on-demand and secure delivery of a generalized computing environment (from a plain desktop, to classroom sized group of users, to cluster of servers, to high-performance computing) to an authenticated and authorized user located anywhere in the world. The system will be engineered such that there is mutual trust between the system, users' data, and the users themselves. Several industry partners (e.g., Red Hat, IBM, Cisco, Nortel) will collaborate with researchers to facilitate technology transfers and conduct joint research. Recently, the researchers at the center have been focusing on developing cost effective security solutions for virtual and cloud computing.

C. Small Business Innovation Research/Small Business Technology Transfer (SBIR/ STTR) Programs

Trustworthy Execution of Security-Sensitive Code on Un-trusted Systems – VDG Inc in partner with Carnegie Mellon University

A Phase I STTR contract was awarded to VDG Inc in 2008 and completed in 2009. A phase II award is expected for the same project. Computing devices are routinely targeted by a wide variety of malware. To use these computing devices with confidence, users need an assurance that the software they run on their computing devices is un-tempered by malware. The STTR academic partner, CMU Cylab, has developed new tools for user-verifiable execution of security-sensitive code on un-trusted platforms in the presence of malware, as shown in the figure below. VDG will mature the technology and make it available to commercial users. The phase I project has successfully built a working prototype that allows the user to verify the status of the computing platform before executing sensitive code.

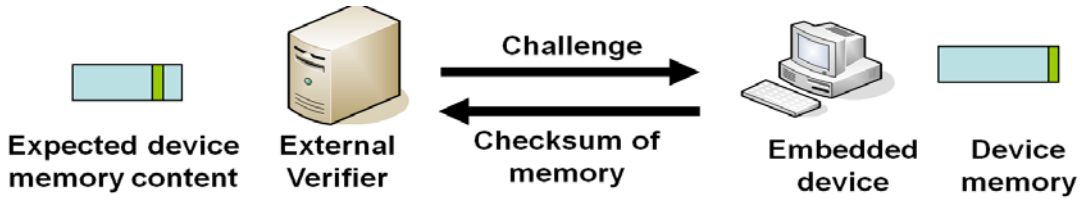


Figure 3. User-Verifiable Execution of Security-Sensitive Code on Un-Trusted Platforms.

Analysis and Visualization of Large Complex Multi-Step Cyber Attack Graphs - Intelligent Automation, Inc. in partner with Penn State University

IAI was awarded a Phase II contract for this project in 2008 and work continues into 2009. The STTR team is developing advanced methodology and tools for analysis and visualization of multi-step cyber attacks against networks. The analysis and visualization engine will be implemented as either a software package for integration or a standalone application. The project will develop new capabilities that information security managers and analysts can use to plan for network hardening, to monitor and analyze active attacks, and to assist post-attack recovery.

Automatic Generation of Robust Network Intrusion Detection Signatures – Reservoir Labs Inc. in partner with University of California, Berkley

This project currently develops a system that autonomously and rapidly: (1) detects exploitation of application software vulnerabilities (including previously unknown vulnerabilities) via dynamic taint analysis, (2) generates vulnerability signatures identifying nearly all traffic that exploits those same vulnerabilities even traffic with no superficial similarities to the observed exploit, and with no false positives via semantic analysis of program paths leading to each vulnerability, and (3) deploys these signatures to a network-based intrusion prevention system to prevent further exploits of the same vulnerability on other systems within the protected network. The system's end-to-end automation will provide effective defense even against rapidly spreading worms spreading via previously unknown (zero-day) exploits.

Automatic Generation of Robust Network Intrusion Detection Signatures - Rether Networks Inc in partner with SUNY Stony Brook University

Network intrusion detection systems (NIDS) provides information to network security analysts on the characteristics of malicious attacks and intrusions in a network, and, in the best case, enable the security infrastructure to be adapted (manually) to current conditions. Unfortunately, it is well know that NIDS suffer from two important problems. First, they commonly have high false alarm rates (both positive and negative) that can significantly reduce their effectiveness. Second, the signatures used to detect new attacks and variants of existing attacks must be crafted by hand after the new attack

vector has been recognized through some other mechanism. This STTR project aims at research and development of a system that can automatically generate signatures for both network intrusion detection systems and network intrusion protection systems.

HYMONT, a Hybrid System Framework for Detecting, Classifying, and Mitigating Malicious Outbound Network Traffic Flows - Milcord LLC in partner with Dartmouth College

The data leak and exfiltration through outbound network traffic flow is a serious threat to enterprise information. Unauthorized outbound traffic as a result of system compromises and espionage, leaks out sensitive or confidential information. Under a Phase I STTR, Milcord researchers have built a hybrid system framework for detecting, classifying, and mitigating malicious outbound network traffic flows of potential data leakage. During the project, they first developed a taxonomy of data exfiltration based on application classes and underlying protocols. In addition, new sensors and traffic classifiers for detecting malicious outbound network traffic flow have been investigated, designed, and built. Performance testing and verification were carried out with regards to metrics such as probability of detection, false alarm and misclassification rates.

Automatic Identification & Mitigation of Unauthorized Information Leaking from Enterprise Networks - Salare Security, LLC in partner with George Mason University

With a wide deployment of VoIP technologies, business corporation and government agencies are facing an increased risk of data leakage and information exfiltration through VoIP communication. Current VoIP protocols and implementation have serious vulnerabilities that adversaries can explore easily to establish a covert channel to sneak out stolen data or information. It is a challenge to carry out deep inspection of VoIP packets for detecting and stopping illicit data exfiltration through VoIP since VoIP traffic is delay sensitive. Further such VoIP communication stream may be encrypted as well. Through this STTR project, Salare Security, LLC addressed research and development of a system that can automatically identify and mitigate data exfiltration (a.k.a data leakage) from unauthorized out-bound voice over IP (VoIP) traffic flows. Statistical models will be built to capture the characteristics of genuine VoIP traffic streams and be used to detect data transmission masquerading as VoIP transmission. Testing and analysis will be carried out using an experiment with live traffic.

Automatic Identification & Mitigation of Unauthorized Information Leaking from Enterprise Networks - Secure Command, LLC in partner with Illinois Institute of Technology

Malicious software or malware and spyware have posed a great threat to DoD information system security. But current available solutions to combat malware are notoriously weak, and they are mostly relying on the on-host anti-virus mode, which detects and determines the presence of malware by searching for known signatures of the spyware executable on the host. This STTR aims at an alternative approach to develop and evaluate novel mechanisms to classify and identify malicious software running in the

enterprise. The new techniques examine program network traffic and automatically generate the appropriate profiles of network behavior for each program. To achieve this, network characteristics of common enterprise applications will be examined and determined by using a set of proxy inspectors at the network edge. Network behavior model will be used to identify abnormal traffic flows. In addition new probing techniques will be developed. Network protocol proxies can be used to probe a host to determine whether the network flow originated from the host is legitimate or is the result of data exfiltration.

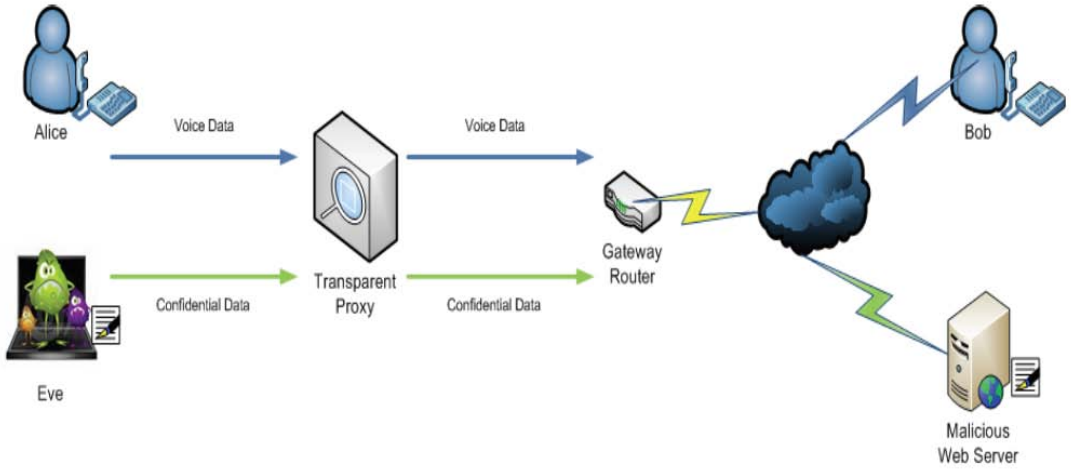


Figure 4. Proxy Inspector at the Network Edge.

Neural ANOVA Information Leak Shunt - WetStone Technologies, Inc in partner with Norwich University

Under this Phase I STTR, WetStone technology and Norwich University combine both proven statistical methods and AI techniques to build new high performance detection capabilities to fight malware invasions. Specifically, they will establish a realistic operational network that they can operate and measure network characteristics under both normal and compromised conditions. Further, the obtained the network statistics will be used to train artificial neural nets for anomaly network traffic detection.

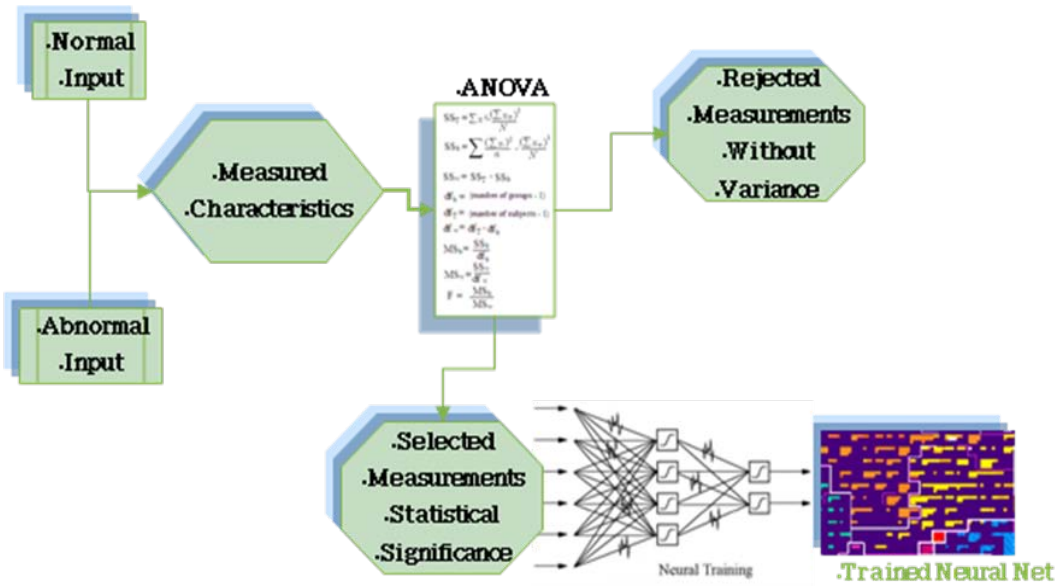


Figure 5. Training Artificial Neural Nets to Fight Malware Invasions.

Modeling Software and Tools for Reliability Engineering of Micro/Nano-Device Systems and Components - Simmetrix Inc in partner with Rensselaer Polytechnic Institute

The goal of this STTR is to define, develop, and implement a set of multi-scale simulation technologies that provide:

- Definition of appropriate models, including inter-scale connection between models that are needed to perform multi-scale modeling of non-equilibrium thermal and shock problems
- A framework to support adaptive control of models in the solution of multi-scale problems
- High-performance computing infrastructure to effectively solve the resulting adaptive multi-scale procedure on parallel computers
- Verification and testing of the resulting capabilities on relevant problems of interest

Robust Multiple Target Tracking - ObjectVideo in partner with University of Southern California

This STTR is focused on developing innovative algorithms and demonstration of a framework for robust and efficient visual tracking using Adaboost-based target detection methods, kernel-based tracker, and robust method for multi-frame data-association. Main technical objectives include: (1) accurate detection of targets, (2) robust online tracking, and (3) persistent tracking of multiple targets across multiple frames. Algorithms will be

validated with thorough performance evaluation and quantitative analysis under different environments and scenarios.

Real-Time Algorithms and Systems for Fused True Color Night Vision Imagery - Opto-Knowledge Systems

This SBIR is focused on developing algorithms and prototype hardware systems for fusing multi-band night vision imagery into a true color display. The end result will be camera systems that use intelligent algorithms in real-time to reproduce day or night scenes in natural recognizable colors. These camera systems will generate enhanced imagery for surveillance and reconnaissance, leading to improved scene understanding and reaction time.

A Physics-based Fusion Approach for Color Night Vision - Spectral Sciences, Inc (SSI)

The objective of this SBIR project is to develop a physic-based approach to color assignment, and a proof-of-principle demonstration of the approach for color night vision that fuses multi-modality images and knowledge of visual color, and to provide reliable and consistent color assignment, and generates images close to natural appearance. To assist algorithm development, SSI will team with Physical Sciences, Inc. in a field measurement program to collect simultaneous hyper-spectral LWIR, MWIR and broadband near-IR imagery of suburban and rural scenes over a wide range of environmental conditions. This effort will also include the development of color rendering algorithm, measurement database, and a conceptual design for a multispectral IR night vision system.

A System to Analyze Facial Features to Enable Operator Condition Tracking (AFFECT) - Charles River Analytics in partner with University of Massachusetts, Amherst

This STTR is focused on the design and demonstration of the Analyze Facial Features to Enable Operator Condition Tracking (AFFECT) system for non-contact classification of Stress, Anxiety, Uncertainty, and Fatigue (SAUF) in interface applications. The AFFECT system combines classification techniques with a multi-dimensional, temporal data model of novel visible and thermal features to enable automatic, non-invasive detection of SAUF conditions in a subject. The development of this technology will in turn enhance training, workflow, and overall effectiveness of war-fighters and analysts.

Real Time Analysis and Fusion of Data from Imagers for Passive Characterization of Stress, Anxiety, Uncertainty and Fatigue - Li Creative Technologies in partner with Rensselaer Polytechnic Institute

The objective of this STTR is to develop a novel solution for real time detection of stress, anxiety, uncertainty and fatigue using passive features from thermal and visual videos of the face. The proposed solution consists of five modules: (1) data acquisition – using

visual and thermal cameras capturing the face images in visible and thermal waveband, (2) facial feature localization and tracking – including the eyes, eyebrows, nose, mouth and their spatial arrangement that detect and track facial features from the face images with different facial expressions under various face orientations in real time, (3) feature extraction and selection based on the facial feature location, extracting the features that are related to SAUF, including expiration rate, heart rate, eyelid movement, head movement, etc., (4) feature fusion and SAUF recognizer based on a dynamic statistical model that can monitor the change in each states and quantify its level, and (5) feedback by the computer to respond to an individual's psychological change by either sending and alarm or offering necessary assistance.

IV. SCIENTIFIC ACCOMPLISHMENTS

The Highly Predictive Blacklisting Service - Phil Porras, SRI International

Researchers at SRI International recently developed a blacklisting system that correlates an attacker's preference for victims' networks as a way to prioritize additions to a blacklist. The algorithm uses link-analysis method similar to Google's PageRank for blacklist formulation. When the system was evaluated using 720 million actual log entries, the researchers found that it outperformed global and local blacklists in more than 80 percent of the cases. Most recently, the blacklisting algorithm was named by PC World magazine as one of the top 10 wicked cool algorithms that both are interesting and have a high impact to our society. This new capability contributes significantly to the nation's cyber defense against attacks from organized crime groups and attacks with nation or state sponsorship.

Figure 6. Link-Analysis Method for Blacklist Formulation

Security Analysis of Network Protocol Implementations - Anupam Datta, Carnegie Mellon University

Industrial network protocols such as SSL, TLS, Kerberos, IPSec, and IEEE 802.11i are designed to enable secure communication over untrusted networks. They have been implemented widely in current networking systems. However, it is extremely difficult to verify the security properties of these protocols. Professor Anupam Datta has leveraged advances in software model checking – a combination of predicate abstraction and model checking with automated abstraction refinement to the problem of security protocol analysis. A framework (ASPIER) has been developed that combines software model checking with a standard protocol security model to analyze authentication and secrecy properties of protocol implementations in an automated manner. Using ASPIER tools, the researchers have successfully analyzed the authentication and secrecy properties of the OpenSSL implementation of the SSL handshake protocol.

Network Vulnerability Assessment Project – Radha Poovendran, University of Washington

Professor Radha Poovendran and his research team have been interested in modeling and evaluating the impact of node capture attacks on the security provided by particular classes of cryptographic key assignment. Due to the unattended operation nature of wireless sensors and other ad-hoc network devices, the nodes are prone to capture attacks, i.e., physically capture and compromise of network nodes. The team has developed a toolkit that enables a user to study the impact of node capture attacks. The toolkit implements a wide variety of key pre-distribution schemes, and allows for significant variations in network and security parameters. Many attack heuristics can be utilized, and the effects can be qualitatively visualized and quantitatively measured on the network.

Multi-Modal Whole-Hand Biometric System - Rob Rowe, Lumidigm Inc.

Under a STTR contract, Lumidigm Inc. developed a biometric system for fast and reliable image capture of the entire surface of the hand that works even under adverse conditions. Such a system will enable the Warfighter and other DoD users to capture a biometric print of the entire hand during a single, rapid placement of the subject's hand on the sensor. The system collects all of the biometric details available from the palm surface of the hand, including fingerprints, coarse and fine features of the palm, and hand geometry - even details from those portions of the hand that are not in direct contact with the sensor. The acquisition system also acquires usable data when the skin is dry or dirty, or the environment is extremely wet or cold, ensuring that the system can be relied upon in field operations and other adverse conditions. Lumidigm has been working closely with the US Army Intelligence Center to get its multispectral imaging biometric technology into the hands of soldiers in the field.

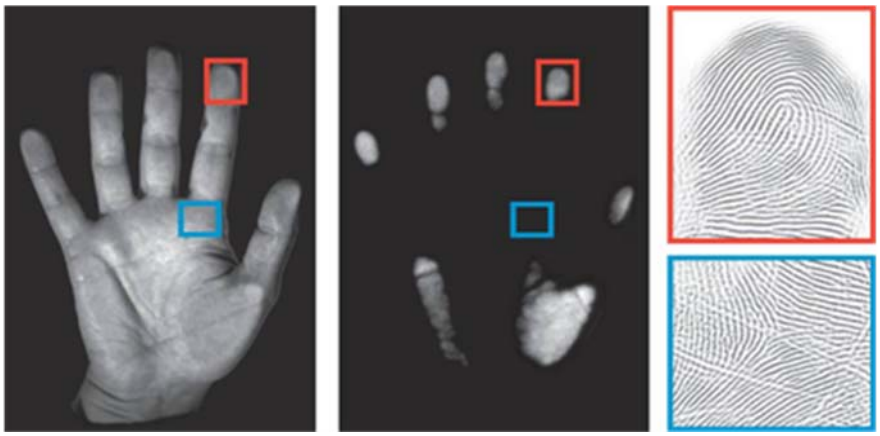


Figure 7. Captured Biometric Features of Whole-Hand System.

Development of New Computational Architectures and Computing Paradigms – Michael Mascagni, Florida State University

A new scalable algorithm for generating quasi-random numbers for simulation and Monte Carlo computations on parallel architectures was developed. This was done through a multi-bit scrambler for the Sobol sequence, based on the randomization of all possible permutations. Its implementation based on the generation of a single Sobol sequence followed by back-end scrambling is very efficient and is close to that of unscrambled sequences, with empirical behavior which is close to optimal. The algorithm has been incorporated into several DSRC libraries and has been shared with several other HPC centers. Work is also maturing on topological mesh methods for modeling shocks and discontinuities in flows. These front-tracking methods combine the advantages of Eulerian methods, applied to volumetric domains, and Lagrangian methods, applied to a lower-dimensional manifold that tracks the front. A library of low-scale mesh topologies and transformations has been developed and coupled with adaptive methods to make possible meshes that exhibit efficient deformation, robust bifurcation and merging, and accurate sub-grid resolution. It also enables multi-physics simulations in the divided volumetric domains. Applications are being developed with WMRD in fracture modeling and with CRRELL on airfoil modeling in the presence of folding and collapse.

Visualization of High Order Finite Element Methods - Robert Kirby, University of Utah, and Bob Haimes, MIT

High-order finite element methods (also known as spectral/hp element methods) using either the continuous Galerkin (CG) or discontinuous Galerkin (DG) formulation, have reached a level of sophistication such that they are now commonly applied to a diverse set of real-life engineering problems. Visualizations of high-order finite element results that do not respect the a priori knowledge of how the data were produced and which do not provide a quantification of the visual error produced may undermine the scientific process as isolating where errors and assumptions are introduced into the process is

critical. The goals of this effort are to define, investigate, and address the technical obstacles inherent in visualization of data derived from high-order numerical methods and to develop algorithms and software solutions that can be employed by the high-order simulation community.

A significant accomplishment for the year was in the area of validation and verification of the visualization of isosurfaces. Visual representations of isosurfaces are ubiquitous in the scientific and engineering literature. The research team designed techniques to assess the behavior of isosurface extraction codes. Where applicable, these techniques allow the user to distinguish whether anomalies in isosurface features can be attributed to the underlying physical process or to artifacts from the extraction process. Such scientific scrutiny is at the heart of verifiable visualization – subjecting visualization algorithms to the same verification process that is used in other components of the scientific pipeline. More concretely, they derived formulas for the expected order of accuracy (or convergence rate) of several isosurface features, and compared them to experimentally observed results in the selected codes. This technique is very practical and in two cases, it exposed actual problems in implementations. Furthermore, the user is provided with the range of responses they can expect to encounter with isosurface techniques, both under "normal operating conditions" and also under adverse conditions. Armed with this information, the results of the verification process, practitioners can judiciously select the isosurface extraction technique appropriate for their problem of interest, and have confidence in its behavior. This is the first time the framework of verification and validation has been applied to assess the correctness of visualization tools.

Physics-based Approaches to Visual Scene Analysis - Todd Zickler, Harvard University

Cameras force a trade-off between resolutions in the spatial, spectral, and temporal dimensions. Typically the spatial and temporal dimensions are sampled densely, and the spectral dimension is observed through a small number of band-pass filters. There is significant interest in reversing the imaging process to infer the latent spectral image from its channel projection. This project has developed a new multi-spectral image model that combines established spatial decorrelation techniques (wavelets, discrete-cosine transforms, filterbanks, etc.) with per-subband spectral basis functions that can be learned empirically. In this new model, the spectral and spatial dimensions are tightly coupled, because the learned spectral basis functions are spatial-frequency dependent. In order to train the model, a light-weight multi-spectral camera has been built and will be used to collect a large database of multi-spectral images of natural scenes.

Automatic Image and Video Annotation - Anil Jain and Rong Jin, Michigan State University

Conventional approaches treat automated image annotation as a multi-label classification problem, with each keyword forming a class of its own. A straightforward approach for multi-label learning is to train a binary classifier for each individual class. The main shortcoming of applying this approach to automated image annotation is that when the

size of vocabulary for annotation is large (i.e., the number of classes is large); it suffers from the imbalanced data distribution in training binary classifiers, leading to poor classification performance. In this project the researchers address this problem by considering automated image annotation as a multi-label ranking problem, in which the goal is to rank annotation words according to their relevance to a given image. A perfect result would rank all the true (applicable) keywords before the other irrelevant words for the given image. Unlike the multi-label classification approach, the multi-label ranking approach is resilient to the size of annotation vocabulary and therefore is applicable even when the number of annotation keywords is very large. The preliminary study with 5,000 images and 100 annotation keywords show that the multi-label ranking framework is significantly more effective than the classification approaches.

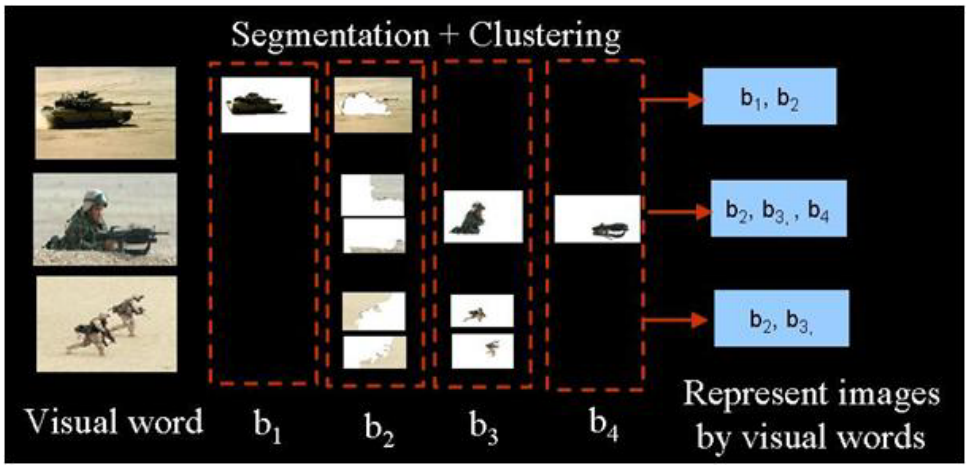


Figure 8. Image Segmentation for Multi-Label Learning.

Multi-scale and Multi-physics Numerical Methods for Modeling Transport in Mesoscopic Systems - Wei Cai, University of North Carolina, Charlotte

Professor Wei Cai, UNC Charlotte, has developed numerical techniques suitable for different physical models in transport in mesoscopic systems such as nano-MOSFET - the key technology in ultra-small devices such as the double gate MOSFET. This year, progress has been made in the numerical methods for three quantum models: (1) Boundary Treatments in Non-equilibrium Green's Function (NEGF) Methods for Quantum Transport in Nano-MOSFET - Non-equilibrium Green's function (NEGF) method is a comprehensive approach to address quantum transport under biased external potential with many body and impurity scattering and device boundary effects. One of the main challenges for numerical simulations is to accurately model the effect of external contact of the device on the electron transport inside a quantum device. Professor Cai has developed a unified treatment of quantum device boundaries in the framework of NEGF for both finite difference and finite element discretizations.; (2) 3-D Time Dependent Schrodinger-Poission Equation With Discontinuous Potentials For Modeling Quantum Dots - In order to model the electron transport property through quantum dots embedded in layered semiconductor materials, the main challenge was to develop an efficient and accurate method to handle high frequency wave scattering and

the discontinuous potential in the 3-D Schrodinger equations.; and (3) A Conservative Adaptive Cell-Average Spectral Element Method for Time Dependent Wigner Equations for Nano-electronics - An alternate formulation for non-equilibrium transport is using the Wigner equation, a quantum analog of classical Boltzmann kinetic theory. The main challenge in this approach is the cost associated with the high dimensional problem in phase space variables (6 for a 3-D device in addition to the time variable). To reduce this cost, a new Adaptive Spectral Element method based on a Cell-Average representation of the Wigner distribution function that allows for the exact enforcement of conservation of electron mass has been developed and is being evaluated in numerical tests.

Adaptive Multiscale Analysis of Deposition Processes - Mark S. Shephard, Rensselaer Polytechnic Institute

Increasingly the models used for many problems of importance must address phenomena occurring on space and time scales ranging over orders of magnitude including electronic, atomic, micro-structural, and system-wide effects. The methods being developed to address these problems face challenging issues including selecting the models for each relevant scale and the coupling information between scales. This project is developing a component-based environment for adaptive multiscale simulation. The focus is on problems that are modeled by PDEs at the largest scale, in combination with continuous and/or discrete finer-scale models describing phenomena at the finer scales in those portions of the domain where such information is needed. Selection of the relevant models requires determination of estimates of the errors introduced by neglecting finer-scale phenomena. This year, an adaptive method for the selection of models in a concurrent multiscale approach was developed. Different models from a hierarchy are chosen in different sub-domains of the problem domain adaptively in an automated problem simulation. A concurrent Atomistic to Continuum (AtC) coupling method based on a blend of the continuum stress and the atomistic force is adopted for the problem formulation. Two error indicators are used for the hierarchy of models consisting of a linear elastic model, a nonlinear elastic model, and an Embedded Atom Method (EAM) based atomistic model. An adaptive strategy is used to obtain results that are providing new insight into the behavior of nano-materials. The results of the technologies being developed as part of this research project are being transitioned to the U.S. Army Research Laboratory (ARL) through a three-way collaboration with Simmetrix Inc. that is supported by ARL to develop various multiscale software technologies.

V. TECHNOLOGY TRANSFER

Professors Virgil Gligor and Adrian Perrig of Carnegie Mellon University have transitioned and matured new technology that can quickly verify the security status of an untrusted platform, and reset the system for assured software execution. During an ARO funded Phase I STTR project, the team developed a fully working prototype and demonstrated the effectiveness of the proposed solution. A phase II STTR project is being planned to bring the technology to users in financial and automotive industry.

Wombat Security Technologies, a new startup company at CMU - Phishing attacks have grown rapidly in the past several years. Yet there were few commercial solutions that were truly effective in this space. Professors Norman Sadeh, Jason Hong, and Lorrie Cranor have developed a phishing email filter that uses advanced machine learning techniques to catch phishing emails. Instead of depending on blacklists and email signatures, CMU's solution leverages advanced machine learning technology and uses heuristics that work from the very start of new attacks. Their research outcome has been recently transitioned to a start-up company Wombat Security Technologies, whose mission is to mature the CMU technology leading to a commercial solution. The CMU researchers serve as founders and senior management team members.

Figure 9. Anti-Phishing Email Filter at CMU.

Professor Agarwal, Duke University and his team have developed software for watershed hierarchy. The comprehensive TERRASTREAM software package is capable of processing datasets of over 500 million data points in a few hours. In FY09 they have modified their TERRASTREAM algorithms and made the package publicly available. It is being used by more than fifty groups in industry, academia, and government agencies worldwide, including UN Environmental Program, Baron Advanced Meteorological Systems, Finnish Geodetic Institute, Icelandic Meteorological Office, City and Landscape Department, Ministry of the Environment, Denmark, and Wildlife Conservation Society, Southern Sudan. A video of their flooding algorithm is available at YouTube (youtube.com/watch?v=7J3sD40vbXQ).

Todd Torgersen and his team at Wake Forest University in their work on Innovative Computational Methods for Inverse Problems in Imaging has contributed to the advance

of important Army technologies in imaging. The need to extract meaningful information from degraded images is especially vital for such DoD applications as integrated optical imaging systems for personnel identification using bio-metrics technology such as iris recognition, as well as other Army applications. In particular, a limited depth-of-focus hampers the performance of traditional iris recognition imaging systems. Sophisticated imaging systems with auto-focus mechanisms can mitigate the issue of depth-of-focus. However, these systems involve noisy motorized mechanisms and lead to system designs that are excessively bulky and expensive. Stringent challenges in cost, platform constraints, and the effective exploitation of the resulting imagery motivate a principled re-examination of the structure, function, and roles of traditional visible and IR cameras for personnel identification and other applications. One of the objectives of this project includes providing novel and extensive research in pupil phase engineering (PPE) in order to help develop a reliable, easy to use, low cost computational imaging system for personal verification for computer network security and other applications. By suitably phase-encoding optical images in the pupil plane and then digitally restoring them, a computational imaging system can greatly improve their quality by removing certain aberrations, such as defocus.

Dr. Gerwin Schalk of Albany Medical College collaborated with researchers at the University of Wisconsin, Madison, to develop and demonstrate a system that allows an individual to send twitter messages by thinking only. Twitter is a free social networking service, similar to texting, which allows users to send and receive short messages. The core component of the system is an electroencephalography (EEG) based brain-computer interface that monitors electrical activity of the brain from the scalp and captures the reaction of the brain to flashing letters on a computer screen. The whole twittering message can be created using this system and sent by thinking the "send" command. The success of this demonstration provides another enabling capability for people with speech disabilities such lock-in users to communicate with others.

VI. DIVISION STAFF

Dr. Cliff Wang, Chief (Acting), Computing Sciences Division
Program Manager, Information Assurance

Dr. Mike Coyle
Program Manager, Computational Architectures and Visualization

Dr. Liyi Dai
Program Manager, Information and Signal Processing

Dr. Joe Myers
Program Manager, Numerical Analysis

I. PROGRAM OBJECTIVES

The principal objective of the ARO Electronics Program is to generate new fundamental knowledge of electro-magnetic, photonic, and acoustic devices, systems, and phenomena in order to provide technological superiority to the Army's future force.

This program will identify and solve the Army's critical basic research problems where progress has been inhibited by a lack of novel concepts or fundamental knowledge. Electronics is relevant to nearly all Army systems; therefore, work under this program has application to a wide variety of developmental efforts and contributes to the solution of technology related problems throughout the full spectrum of the Army's "System of Systems." Research under Electronics for the fiscal year 2008 can be divided into five general application areas below:

- **Multimodal Sensing** – Sensors and supporting circuitry for detection, identification, and discrimination of battlefield environments, including enemy and friendly elements and their activities. Multimodal includes, but is not limited to, acoustic, seismic, magnetic, infrared, ultra-violet, and RF sensors in both active and passive mode. The ultimate goal is 100% situational awareness: day/night, all weather, multi-modal, multi-spectral sensing of vehicles, personnel, weapons, chemical and biological threats, projectiles, -explosives, landmines, IEDs, and motion; to include non-line-of-sight and through natural and man-made obstructions.

- **Ubiquitous Communications** – Multimode and secure communications in all situations and addresses extremely high data rates, transmission over long distances and complex terrain paths, as well as problems associated with short range networked systems. Technology areas include RF, optical, and acoustic transmission. Research includes propagation, device and circuit architectures, and waveform engineering. The ultimate goal is to communicate seamlessly and covertly with friendly elements in all physical environments and weather while on the move.

- **Intelligent Information Technology** – Technology that enhances the creation and processing of information. This includes hardware and architecture improvements to process information faster, up to fundamental limits, involving miniaturization and new modalities, such as spin electronics, bio-molecular electronics, and parallel optical processing. Also includes signal processing, sensor fusion, and algorithm development for specific hardware implementations.

- **Optoelectronic Warfare** – This involves the use of electromagnetic radiation, from RF to infrared, to interrogate, disrupt, and defeat hostile electronic and threat systems. It includes remote interrogation of electronic systems and disruption of their intended use by electromagnetic signals. It also includes advanced solid state lasers that have very high CW power output (> 100 kW) to defeat incoming

projectiles and missiles, or that operate in a specific band to defeat targeting sensors of various threats.

- **Power Electronics –** Electronic circuits and components that require less power and/or operate in extreme conditions. Both high power and low power, energy efficient devices are needed. Non-chemical techniques to create efficient, light weight power sources are also included. The main objectives of this thrust are to lighten the soldiers load and to ensure that no blackouts occur during Army operations.

II. RESEARCH PROGRAM

A. General Information

The Army Electronics Program consists of a combination of needs and opportunity driven research. In some cases the needs-driven research projects originates with a highly directed search effort, for example, a customer funded project to study the feasibility of disrupting the functions of wireless devices via "shaped" electromagnetic waves. In other cases the projects arise from the discovery of a unique opportunity that fits a known need, as the discovery that a quantum cascade laser could be used in reverse as an infrared detector. The pure opportunity research areas tend not to be driven by specifically recognized Army needs. Some can have an immediate indirect impact on Army systems, such as new algorithms and devices that enhance and speed up computer processing. Others can result in future systems requirements once the unforeseen technical capability has been demonstrated and analyzed, for example, new opportunities for room temperature spin semiconductor devices.

The Electronics Division research includes the exploration of new or improved operating principles of electronic devices to provide new performance opportunities and greatly improve performance and reliability of existing devices. Studies of the fundamental limitations of the operating ranges of devices will provide direction for potential improvements. Part of the research effort is the evaluation of phenomena that limit the performance of existing devices. Other phenomena involve the generation, detection, and processing of electronic signals.

B. Trends/Workpackages

ARO's Electronics Division is subdivided into six workpackages or research themes as named below:

1. Solid State and High Frequency Electronics
2. Optoelectronics
3. Quantum Electromagnetic Devices
4. Electromagnetics and RF Circuit Integration
5. Novel Electronic Devices – Sensors and Detectors
6. Power Electronics

Further information about the Electronics program can be found at the ARL Electronics Division website at http://www.arl.army.mil/www/default.cfm?Action=29&Page=193.

C. Research Investment

The FY09 allotment for the ARO core electronics (BH57-09) program was $5.1 million. The Army Materiel Command Research, Development and Engineering Centers (RDEC) and other services and agencies provided an additional $0.5 million. The Department of Defense Multi-disciplinary University Research Initiative (MURI), Defense University Research Instrumentation Program (DURIP) and DEPSCOR provided $5.4 million. ARO electronics engineers managed $12.7 million for the Defense Advanced Research Projects Agency (DARPA), $1.1 million for the Defense Threat Reductions Agency (DTRA), $1.7 million for the Joint Technology Office (JTO), and one congressional for $3.7 million. The Small Business Innovative Research (SBIR) and the Small Business Technology Transfer (STTR) programs provided $7.6 million. Congressional and other investments bring the Electronics total for FY09 to around $40 million.

D. Workshops and Symposia

Workshops, seminars, and symposiums are organized and sponsored by the Electronics Division with the purpose of assisting the recognition and stimulating the formulation of planned program thrusts that respond to technological opportunities and Army needs. Army laboratory scientists, as well as, ARO scientists attend these activities. Examples of such meetings include:

- Symposium on "*Rare-Earth Doping of Advanced Materials for Photonic Applications*" – Part of Material Research Society Fall Meeting, Boston, MA, November 2008.
- XXX General Assembly of the International Union of Radio Science (Union Radio Scientifique Internationale-URSI), 5-8 January, 2009, Boulder, CO
- 2009 International Conference on Quantum Structure Infrared Photodetectors (QSIP), January 18-23, 2009, Yosemite, CA.
- 2009 IEEE Radio and Wireless Symposium, 18 - 22 JAN 2009, San Diego CA
- The Summit of NAE Grand Challenges, 2-3 MAR 2009, Durham, NC.
- 215th Electrochemical Society Meeting**,** May 23-24, 2009, San Francisco, CA
- Advanced Research Workshop on Future Trends in Microelectronics: Unmapped Roads, 14-19 June 2009, Villasimius, Sardinia, Italy
- ARO-JTO Workshop on "*Future Directions of Fiber Lasers*", Hartford, CT, September 2009.
- ARO Workshop on *"Impurity Based Electroluminescent Devices & Materials II"*, Tossa, Spain, September 2009.
- 33nd Antenna Applications Symposium at Allerton, 22 - 24 SEP 2009 in Monticello, IL.
- 2009 Conference on Nanoelectronic Devices for Defense and Security Sept 28-Oct 2, 2009, Ft. Lauderdale, Fl.

III. SPECIAL PROGRAMS

The Electronics Division supports consortia/center of excellence programs. These programs focus substantial university effort upon topics of critical interest to the Army.

Multidisciplinary University Research Initiative (MURI)

A MURI is a DoD-funded program to perform research and develop technologies in areas of importance to future DoD programs. MURI awards are typically on the order of one million dollars per year for a three-year base period, with additional options for two years for programs demonstrating significant achievement.

A MURI on **Human Signatures for Personnel Detection** was awarded to Georgia Tech in June, 2004. This MURI will institute a theoretical and experimental treatment of the basic human signature phenomenology to provide a firm scientific basis for future personnel detection studies. It is anticipated that this scientific base will be used to guide sensor system development and detection techniques of personnel in complex environmental and terrain conditions. This MURI is chiefly concerned with personnel detection and discrimination from other objects and animals, and less concerned with personnel identification or intentions of the people. Four tasks will be worked on: (1) Human Signature Phenomenology Study to include many different types of signatures, such as: acoustic; seismic; radar (RF to millimeter wave) and passive electromagnetic; active and passive EO/IR (electro-optic and infrared); hyperspectral, etc. (2) Sensor Fusion and Networking Study to decrease the probability of false alarms and increase the effective range of a sensor system. (3) A New Sensor Concept Study which will exploit the results of the phenomenology study and may include a different modality, and (4) Multi-Sensor Data Collection. A MURI review was held on July 9 at the Georgia Tech Washington office in Rosslyn, VA and was attended by eight government board members, Clark and Dai from ARO, Gillespie from SEDD, Farwell from I2WD, Royston from ONR-SAIC, Larkin from AFOSR, Szu from NVESD, and Quoraishee from ARDEC. The team at Georgia Tech is trying to create an infrared model of an urban scene with personnel and vehicles in motion. In the past year they showed individual models for persons walking, including the difference between female and male; vehicles in motion, a building, and the integration of all three. In the acoustic area Jim Sabatier of the University of Mississippi developed an acoustic modeling of a person walking which consisted of adding the signals from 13 moving parts of a human. The composite signal agreed well with measurement. He also compared four different “orthogonal” sensor responses from a walking human inside a building and along a trail. The four sensors were active sonar, passive ultrasonic microphone, low cost radar, and geophone. This MURI has created opportunities for Professor Sabatier of Mississippi to work with ARL and he will become an IPA at SEDD for an extended time to continue to work on human detection as well as vehicle and tunnel detection. Dr. Hersey of Georgia Tech expanded his model of the radar return from a person walking to consider the real world case of fluctuating velocity. He was able to show that linear phase filters were inadequate for detection of a walking person with noise and ground clutter. Using higher order filters (quadratic, cubic, and, especially sinusoidal) plus post detection integration

(PDI) he was able to make significant improvements in personnel detection with radar. Bill Rhodes at Florida Atlantic University has been working on detection of humans using low resolution video. His current work makes use of the contextual scene information to detect and track a moving human. His algorithm was able to detect and track a moving human even when the human was partially obscured. Charles Rhors of MIT developed a new method of estimating transfer functions between sensors to perform blind equalization with much better noise properties. Blind equalization is a way to recombine separate partial sensor signals to retrieve the original signal in total. He also devised a new method to reconstruct randomly jittered signals.

The MURI program on **Standoff Inverse Analysis and Manipulation of Electronic Systems** (SIAMES) started in 2005 with two funded efforts: one at Duke University, and one led by North Carolina State University (NCSU) with teams from Purdue University and the University of Illinois at Urbana-Champaign (UIUC). The primary objective of the SIAMES program is to enable detection and classification of wireless IED detonators and other radio transceivers at operational tempo and standoff distance using radio wave interrogation. This requires the development of tools and techniques in microwave circuit and system design, signal processing and signature extraction, and data analysis, manipulation, and display. The research output of this MURI has the potential to dramatically and fundamentally change the design, construction, and concept of operation for a wide range of military and commercial communications, sensor, and imaging systems.

The UIUC team has developed a fast algorithm for numerical simulation of multi-tone electromagnetic waves. Through the application of recent advances in methodologies for the solution of multi-time partial differential equations, this algorithm provides for a 10-100x increase in the computational efficiency of the simulators used for the modeling of electromagnetic propagation and interaction of multi-tone waves, in which the frequencies of the contributing signals exhibit large disparities in periods in the order or 10 or even 100. This algorithm has the potential to increase significantly the computational efficiency of computer tools and simulators used for a) the computer-aided design and prototyping of RF/microwave components used in communication electronics; and b) the computer-aided analysis and optimization of the performance of robustness and channel bandwidth efficiency of the broadband communication networks used in support of battlefield operations.

By making use of the periodic extension of band-limited frequency responses, the UIUC team also has developed a methodology that allows us to render causal the impulse response of a multi-port, passive electromagnetic network, described in terms of rational function interpolations of band-limited frequency response data, obtained either through measurement or numerically through the application of an electromagnetic field solver. This methodology ensures the causality and passivity of rational function representations of RF/microwave passive components, which constitute the behavioral descriptions of the electromagnetic attributes of these components in general-purpose, network analysis oriented circuit simulation tools (e.g. ADS, Microwave Office, SPICE-based simulators)

thus enhancing robustness and accuracy of these simulators in their use for the computer-aided analysis and design of communication electronics.

Two Ph.D. students from North Carolina State University supported under the SIAMES MURI participated in successful summer internships, one conducting research on measurement of nonlinear microwave phenomena in the ARL/SEDD RF Signal Processing and Modeling Branch at Adelphi MD, and one developing distortion cancellation equipment in the Intelligence and Information Technology Directorate of the Communications and Electronics Research, Development, and Engineering Center at Ft. Monmouth NJ. One student has been offered and has accepted a full-time S&E position with ARL/SEDD upon graduation in the fall of 2009. Both brought value to the hosting organizations and to their university through direct experience with Army research and development activities.

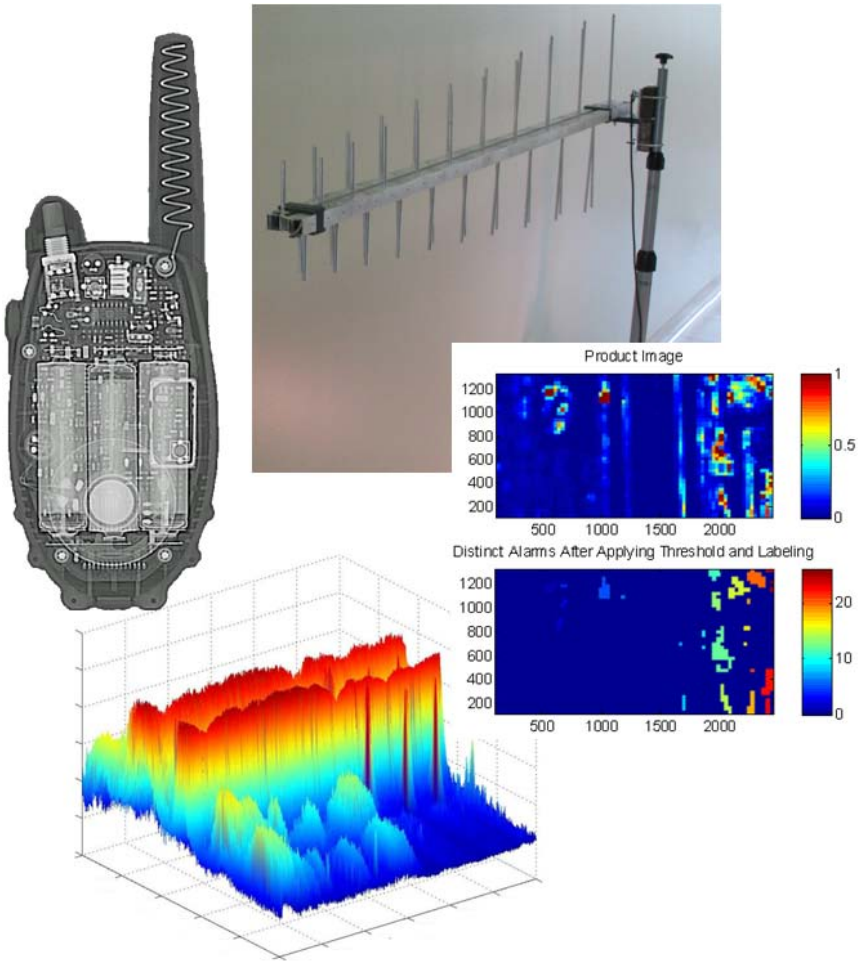


Figure 1. (Counter-clockwise from upper right) Antenna on conceptual SIAMES system scans the circuitry in a radio, producing a spectrogram signature. The signature is analyzed, compared to modeled responses, and used to present a visual display of threats to the warfighter.

A Joint Technology Office (JTO) multidisciplinary research initiative (MRI) entitled **A Dynamic Approach to High Power Fiber Laser Arrays** was awarded to Professor Kurt Wiesenfeld of Georgia Institute of Technology in 2005. The major goal of this JTO MRI was to develop a fundamental dynamical understanding of coherent beam combining of fiber lasers. Previously, the primary concepts centered on the static compound-cavity modes, typically in the cold cavity limit. Professor Wiesenfeld's approach has been to develop dynamical equations that embody the essential physics that describe the interplay between electric field and atomic gain degrees of freedom of the fiber lasers. He has created a simple yet quantitatively accurate dynamical model that is extremely fast to simulate beam combining situations. His model has able to explain, for the first time, the cause of pulsing instability that has been observed experimentally in 4-level fiber lasers. He has also developed a theory of gain-dependent phase shifts, which may be the key to synchronization of high power fiber lasers. The very large number of active longitudinal modes inherent to these lasers may set limits to scalability of power combining schemes. On the experimental side, his group has made the first demonstration of the advantages of patterned pumping, and of a novel strategy of patterned applied-losses. They have made the first direct tests of the "modal winnowing" hypothesis to explain observations of decreased power combining efficiency with increased array size. These accomplishments were made possible by advanced experimental diagnostic capabilities in his lab; see Figure2, for power combining fiber arrays. These include detailed resolution of the full longitudinal spectra; and simultaneous dynamical monitoring of spectra, output intensities, and far field patterns. Future directions center on creating a fundamental dynamical theory to include multiple longitudinal modes and on tests of promising strategies to manipulate the modal spectra. High average power fiber lasers will enable multiple high-level DoD mission capabilities for rapid force protection, dominant maneuver, and full dimension protection. They will provide speed of light engagement capability with flexible response against enemy missiles and rockets.

Figure 2. Experimental set-up for coherent beam combining of up to eight fiber lasers. Diagnostic capabilities include resolution of the full longitudinal spectra and simultaneous dynamical monitoring of spectra, output intensities, and far field patterns.

A Joint Technology Office (JTO) multidisciplinary research initiative (MRI) entitled **High Power Fiber Laser** was awarded to Professor John Ballato of Clemson University in 2005. The major goal was to develop eye-safe 10 kW fiber lasers. The focus on new materials and fiber designs is generally divided into three main areas: enabling materials, modeling, and fiber and laser development. In the fourth year of this program the most significant findings were primarily in the Tm doped silica fiber research. Other than the >100 W demo made in years 2 and 3, research this year has focused on use of VBGs (Volume Bragg Gratings) and GMRFs (Guided Mode Reflectors) for narrow linewidth and tunable demonstrations. Tunable lasers with 50 pm linewidths and tuning ranges of 50 nm were demonstrated using angle tuning with VBGs. Spectral beam combining (SBC) of three laser wavelengths was shown with GMRFs. Other research in gain-guided lasers has progressed slowly due to problems in fabrication of specified fibers. Past work in the MRI yielded lasing in 100, 200, and 400 micron core fibers with an output approximating the lowest order mode. Scaling of the laser power in these waveguides will take a great deal of further investment to develop the fabrication capability for these special fibers. Stimulated Brillouin Scattering (SBS) threshold for such lasers is over 1 MW. Beam quality factors (M^2) of 1.8 have been demonstrated thus far for the 400 micron core fiber.

The development of efficient high average power fiber lasers will enable multiple high-level DoD mission capabilities for rapid force protection, dominant maneuver, and full dimension protection. They will provide speed of light engagement capability with flexible response against enemy missiles and rockets. Such laser systems will also produce improved remote sensing, ranging, and designation.

A MURI at Pennsylvania State University on **Uncooled Materials for Infrared Detection** was started in FY2006. Professor Mark Horn is the Principal Investigator of a team that also includes researchers from Ohio University and the University of Toledo. This MURI was funded as a Cooperative Agreement between Penn State, NVESD, ARL-SEDD, and ARL-WMRD. In addition, ITAR agreements are in place that allows industry collaborations with BAE Systems, DRS, and L-3 Communications. This effort is exploring the fundamental issues impacting the use of thin film bolometric materials for monolithic silicon microbolometer arrays. In particular, their goals are to improve the temperature coefficient of resistance (TCR) and decrease the time constant as well as discover methods that mitigate the problems of spatial non-uniformity, 1/f noise, and image retention in the current materials. They are investigating current bolometer materials, vanadium oxide compounds (VOx) and alpha-silicon, as well as some new materials such as spinel. The fourth review was held on August 31 at the OSD-DDRE office in Arlington and well attended by 22 industry and government representatives. Most of the presentations were given by students who were well prepared and excellent speakers. The highlights were: (1) “good” properties for infrared detection using VOx seem to be found in materials with crystalline FCC structure but with a stoichiometry around x=1.8. This does not match the phase diagram for VOx. Thus, it was proposed to be a composite structure of nanocrystalline and amorphous material. Electron diffraction and Raman spectroscopy seem to support this hypothesis. The following figure shows the thin line separating amorphous and nano-crystalline microstructures for different

compositions and growth conditions. In addition, TEM showed that growth of VOx starts with a thin layer of disordered (amorphous) material before the microcrystallites begin to form. (2) Raman spectroscopy also showed that films can have different microstructure and composition and still retain similar electrical properties. It was also shown that ε_2 dielectric coefficient obtained by spectral ellipsometry (SE) correlated with the resistivity of VOx. (3) Transport modeling indicated a possible mechanism for the difference between α silicon and VOx: α silicon can use conduction band and hopping, while VOx only uses hopping. Nanocrystals also affect transport at high fields. (4) Spinels were successfully deposited by spin spray mechanism which is more cost effective than other methods. Spinels grown by sol-gel method were shown to have high TCRs and were very stable. The stability makes it an interesting material. (5) The ZnO pyrofet work is progressing but still needs to be grown on an isolation structure. One advantage it may have is ability to be grown on curved surface. This could reduce cost of optics. (6) In the α silicon/germanium work the electrical properties (TCR and resistivity) were correlated to the microcrystallinity. 1/f noise also seemed to vary directly with the degree of microcrystallinity.

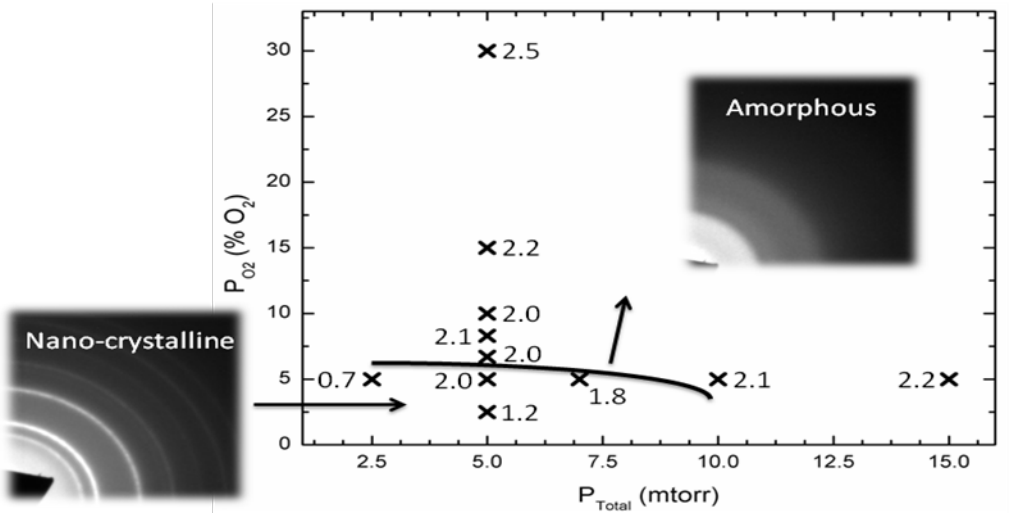


Figure 3. Composition and microstructure of magnetron sputtered films of VOx.

Other Programs: SBIR, STTR, HBCU/MI and Other Initiatives

Nanostructures for Dislocation Blocking - Dr. Ishwara Bhat, Rensselaer Polytechnic Institute

Current state of the art Long Wave Infrared (LWIR) and Very Long Wave Infrared (VLWIR) focal plane arrays are typically fabricated with HgCdTe epilayers grown on expensive and limited-size CdZnTe substrates. The transition to silicon-based substrates, which are much cheaper and available in large sizes, has been hindered by high dislocation densities in HgCdTe epilayers resulting from lattice mismatch-induced strain. Dr. Ishwara Bhat at RPI is working on an STTR project with Sudhir Trevedi of Brimrose

Corporation of America to grow CdTe thin films via Metal-Organic Chemical Vapor Deposition (MOCVD) on silicon wafers containing CdTe nanocrystals/quantum dots. The rationale is to produce strain using nano crystals of CdTe that would then lead to threading dislocations, which would bend in a random manner such that the Burger Vectors of dislocations at various strain fields would annihilate, thus decreasing the overall dislocation density to $10^5/cm^2$ or less. In the past year he has investigated the MOCVD conditions necessary to deposit a germanium buffer layer on silicon [(111) and (211)] before the nanocrystallites are spun on. Highly specular Ge films with good surface morphology resulted after several tries and single crystal orientation of Ge was verified by X-ray diffractometry. He also optimized experimental conditions for selectively growing CdTe on patterned (211)Ge/Si wafers. The patterning was achieved by oxidizing the silicon under a mask. The figure shows the results of this work.

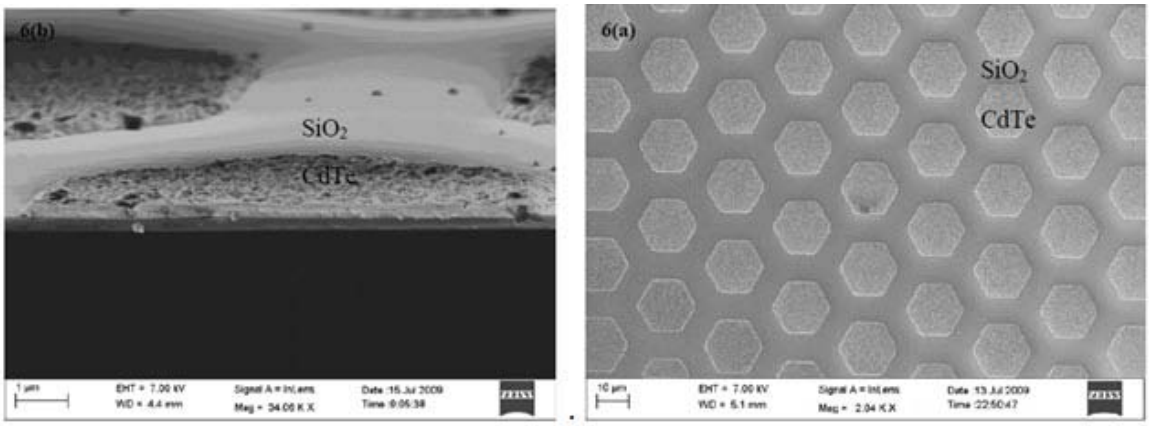


Figure 4. SEM image showing selective growth of CdTe at 475 deg. C in the patterned posts. Perfect selectivity is evident even for large size patterns.

Hybrid Organic/Inorganic Light Emitting Diodes – Professor Shanthi Iyer, North Carolina A&T State University and Jay Lewis, Research Triangle Institute

A Cooperative Agreement between NCA&TSU and the Army Research Laboratory was established in FY05 to perform research on *Environmentally Stable Flexible Displays.* Professor Shanthi Iyer is leading efforts at NCA&TSU to grow low temperature GaNAs thin films on various substrates for electronic devices. Dr. Jay Lewis at the RTI has been depositing various organic materials for development of a new class of organic/inorganic hybrid light emitting diodes. Recent research findings indicate promising results in the development of hybrid organic/inorganic light emitting diodes (LEDs) using zinc oxide (ZnO) as the cathode material for injection of the charge carriers. The use of ZnO films is currently emerging as a potential alternative to indium tin oxide (ITO) films due to its competitive electrical and optical properties. In addition, ZnO films have further advantages in low price, abundance of raw material, and nontoxicity. A magnetron rf sputtering unit has been installed in Dr. Iyer's lab and synthesis of ZnO thin films has begun in conjunction with current work on the wide band gap III-V materials by MBE.

This Cooperative Agreement is part the Center of Excellence for Battlefield Capabilities Enhancements program.

Self-Assembly Production of Hybrid CMOS/Nanodevice Interconnects – Dr. Richard Claus, NanoSonic Inc.

Dr. Richard Claus has made significant accomplishments in developing and demonstrating a novel spray-based self-assembly process which has been combined with Virginia Tech's holographic interference-based lithography to realizing integrated electronic and photonic systems of high relevance and importance to the U.S. Army and DoD. Two noteworthy accomplishments include: (i) the successful development of prototype large arrays (e.g., 16x32 or 512 elements) of thin film transistor (TFT) on both silicon and polyethylene terephthalate (PET) flexible substrates; and, (ii) the development of a new type of "display fabric" which organizes the pixel elements into a semi-transparent material matrix. These collective accomplishments illustrate the significant technological potential of the evolving electronic materials and devices project which has also already resulted in $2M in product sales to major U.S. Defense contractors (e.g., Lockheed Martin and Raytheon).

Figure 5. (left) Thin Film Transistor Arrays on a PET Substrate; Many-Element Display Device Exhibits Imaging Properties (Middle), and Mechanical Flexibility (Right).

UV Light Emitting Diodes – Dr. Jinwei Yang, Sensor Electronic Technology, Inc.

A phase I SBIR program demonstrated technical feasibility for development of high-power, large-area deep UV LEDs and fabricated record breaking single chip device with peak emission wavelength in the range of 270-275 nm and output power exceeding 50 mW. This SBIR Phase I project demonstrated the technical feasibility of high power and long lifetime single chip large area (> 1mm x 1mm) DUV LEDs with ~5x improvement of peak CW power over standard small chip UV LED. Phase I development also included growth of low defect density high Al-content thick template layers by migration enhanced metalorganic chemical vapor deposition (MEMOCVD®) over patterned sapphire substrates; laser-assisted lift-off of the sapphire substrate; and fabrication of 2D photonic crystal (PC) structures using aluminum anodic oxidation process. Large area single chip DUV LED devices fabricated during this Phase I project will be subject to extensive reliability and thermal tests during Phase I Option. The technology developed

during Phase I effort will be further improved and implemented in fully packaged high power DUV LED device, which will be tested, optimized and scaled-up for production in Phase II.

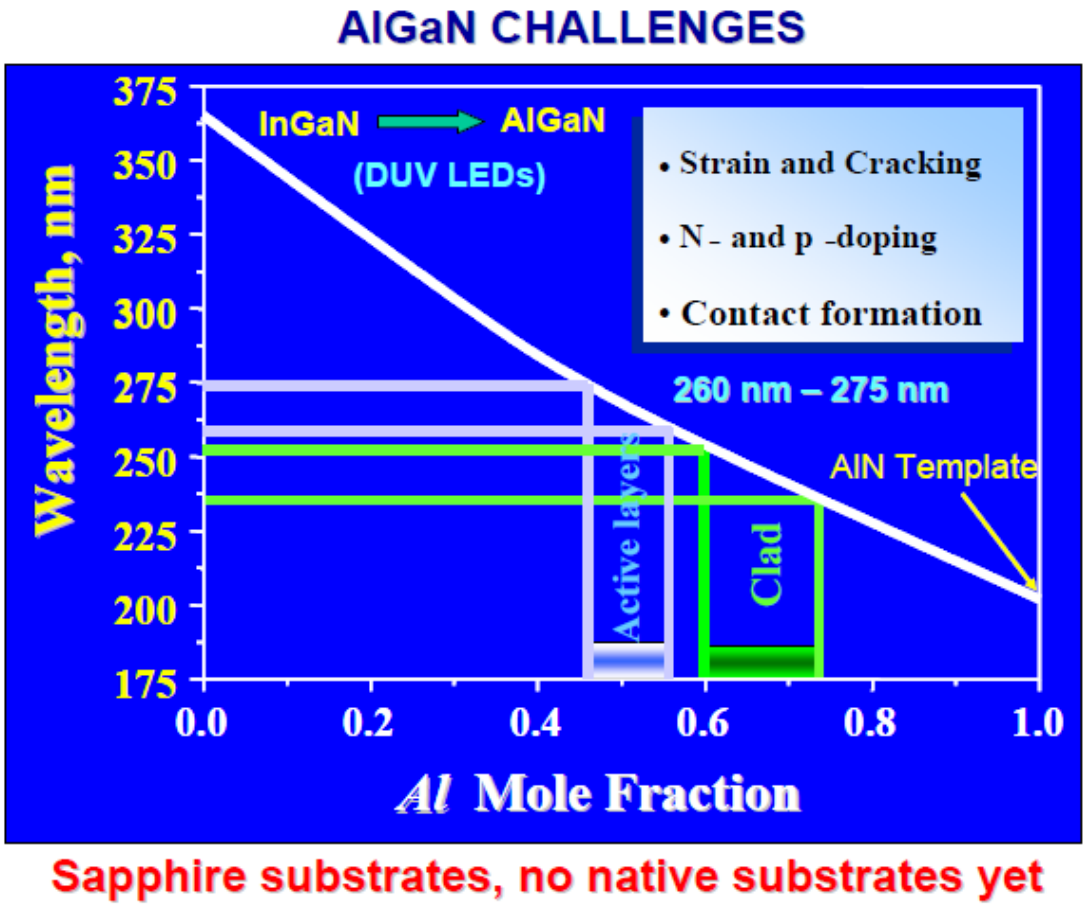


Figure 6. Output wavelength vs. Aluminum (Al) mole fraction in the quantum well of the AlGaN alloy heterostructure LED.

Multifunctional Antenna Techniques – Professor Gregory Huff, Texas A&M University

Professor Huff is working under a Presidential Early Career Award for Scientists and Engineers (PECASE) grant with Texas A&M University to develop multi-scale design methodologies and system-level integration techniques that functionalize antenna elements, antenna arrays, and sensor technologies into transformational technologies for multifunction systems. To this end, the project will investigate bidirectional electromagnetic apertures integrated into platforms to balance the practical constraints of emerging RF applications spanning a frequency range from 2 MHz to over 100 GHz, and system-level techniques that maximize the impact of these technologies. The analytical methods, experimental investigations, and design methodologies developed in this work will reflect this primary goal through the innovative operation of novel apertures and

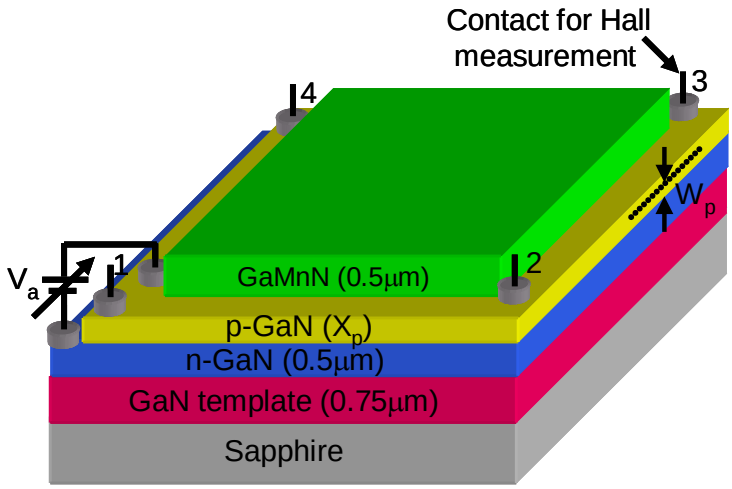
proof of concept demonstrations that will facilitate the transfer of these technologies into Army-relevant applications.

The research will be implemented based on three major thrust areas: (1) examine the functional balance between bandwidth, size and weight limitations in VHF and UHF apertures for multifunction platforms, (2) explore the combination of mm-wave apertures and dense sensor arrays as integrated electromagnetic and structural reconfiguration mechanisms, and (3) investigate and develop the analytical framework for dynamic networks of platform-integrated antennas with integrated sensor technologies. Successful completion of the research program will improve Army capabilities in and develop new tactical antennas for military wireless communications, radar, and sensing systems.

IV. SCIENTIFIC ACCOMPLISHMENTS

Electric Field Control of Ferromagnetic Behavior of GaMnN Thin Films at Room Temperature – Professor Nadia El-Masry, North Carolina State University

Professor El-Masry's research team has achieved a key milestone in developing a new type of dilute magnetic semiconductor (DMS) material that offers substantial gains in electronic and magnetic functionality. This material involves doping of manganese (Mn) atoms into gallium nitride (GaN) epilayers during growth by metal organic chemical vapor deposition Magnetic measurements were done at room temperature (300 K) in Professor El-Masry's lab using an alternating gradient magnetometer. Depending upon growth parameters certain epilayers exhibited hysteresis behavior indicative of ferromagnetism, while others did not. Through systematic studies, Dr. El-Masry was able to formulate a model for the ferromagnetic activation of Mn ions in GaN in which the whole conductivity in adjacent layers played a critical role. A multilayer test structure was designed and recent experiments have demonstrated that the magnetic behavior can be electrically modulated using an applied bias on the structure producing a transition from paramagnetic to ferromagnetic behavior. A National Research Council post-doctoral fellow, funded by ARO, was part of the research team conducted these experiments. Such devices, with room temperature electrical control of ferromagnetic behavior have important applications in non-volatile memory storage systems and on the field of spintronics. This emerging technology enables a semiconductor to make use of electron spin as well as the charge characteristics to increase the functionality of microelectronic devices. While previous experiments have yielded functional prototypes of spin-electronic devices, they could function only at cryogenic temperatures.


Contact for Hall
measurement
4
3
W_p
V_a
1
2
GaMnN (0.5μm)
p-GaN (X_p)
n-GaN (0.5μm)
GaN template (0.75μm)
Sapphire

high-speed LEDs would be easy to mass produce and could be used for many data transmission and interconnect schemes well into the future. Details of the device designs and performance can be found in June 12 and 15th issues of Applied Physics Letters. Applications of HBLETs for the Army could include chip-to-chip or inter-board communications for short haul networking.

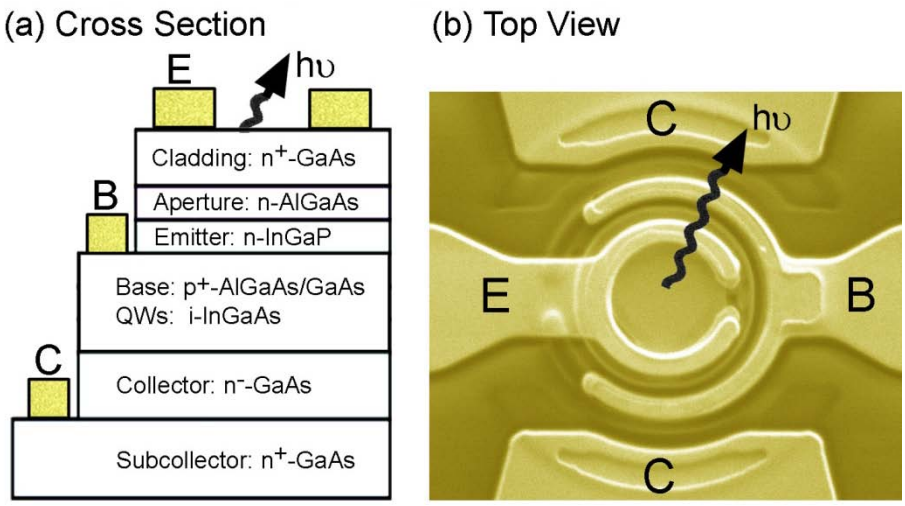


Figure 8. (a) Cross section of heterojunction bipolar light emitting transistor (HBLET) (b) Top view of HBLET

1st Type II Photodiode by MOCVD – Professor S.L. Chuang, University of Illinois at Urbana Champaign

InAs/GaSb type-II superlattices (SLs) are a promising material system for middle infrared (IR) applications and photodetectors based on these SLs have been demonstrated exclusively by molecular beam epitaxy (MBE). The MBE is prominent in the control of layer thickness. However, an island-like defect is sometimes formed in MBE growth. On the other hand, metal organic chemical vapor deposition (MOCVD) is excellent for the flatness of the interface between alternating layers because MOCVD is a deposition method based on a chemical monolayer adsorption and thermal decomposition. S.L. Chuang of UIUC and Russell Dupius at Georgia Tech have demonstrated MOCVD grown InAs/GaSb type-II superlattice photodiodes for the first time. Their results are about 2 orders of magnitude less than those from MBE but there were several manageable problems in fabrication that were encountered in their first try. These include undercut mesas due to poor sticking of the photoresist, high contact resistance, and no sidewall passivation. Thus, it is most likely that the performance of the detectors can still be improved using the current material samples. Also, quantum cascade detectors based on the InP material system will be attempted because of easier growth by MOCVD.

Biomolecular Detection and Spectroscopy Using Plasmon Waveguides and Nanowire Fet Detectors – Professor Mark Reed; Yale University

Recent progress has been made on the development of integrated plasmonic devices with simultaneous excitation and detection capabilities. Specifically, this effort excited and detected plasmonic interactions using conventional far-field optical microscopy and made observation in an electrical detection system based on semiconducting nanowires. As illustrated below, the research project successfully fabricated hybrid devices and excited plasmons in a metallic nanowire deposited across a semiconducting nanowire. After excitation (850 nm) on the end of the silver nanowire on the left (bright spot), emission is visible at the distal end (far right) due to rescattering into photon modes. This rescattering into light has been observed previously for metal-metal junctions, but not for a metal-semiconductor junction, and this work points the way to integrated system.

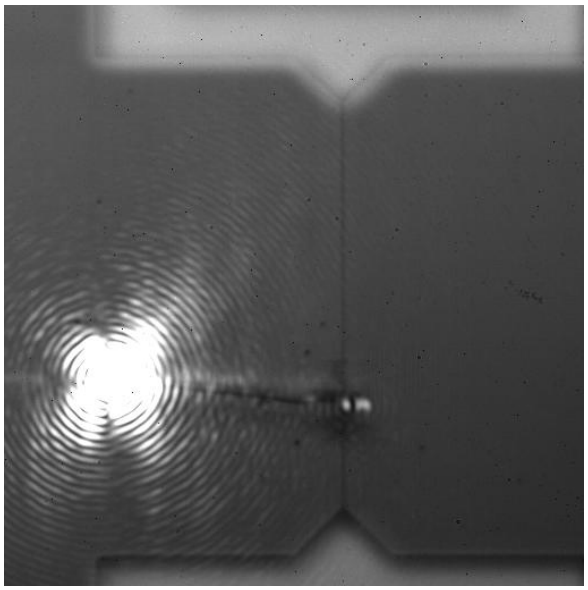


Figure 9. Hybrid Nanowire Device Exhibiting Rescattering-Based Plasmon Propagation.

Infrared Tunability of Intersubband Absorption in GaN/AlGaN Superlattices – Professor Manijeh Razeghi, Northwestern University

The III-V nitride semiconductors are very attractive materials for the development of novel intersubband (ISB) devices. Since these materials are unipolar, ISB transitions allow for fast carrier relaxation process as well as wide-range optical tunability from near-infrared to THz regions. In addition, the high electronic effective mass and the large longitudinal optical phonon energy make these materials suitable for high speed and high temperature ISB applications. In work sponsored by DARPA, Professor Razeghi's research team has been growing multilayer GaN/AlGaN structures using metalorganic chemical vapor deposition (MOCVD) techniques. Critical issues concern interface quality and thickness control of individual layers over the entire AlGaN/GaN multilayer

structure. High quality AlN/GaN structures were grown, processed, and absorption at optical communication wavelengths (from 1.5 to 2.2 microns) was measured. This is the shortest wavelength absorption reported for MOCVD grown material. An analytical model, including internal field, energy-dependent effective mass, and envelope function approximation, was developed and a novel MOCVD deposition technique was introduced to permit absorption at longer wavelengths. Recently, structures were grown and absorption at wavelengths from 4.5 to 5.3 microns was demonstrated as shown in figures below. Effects of growth temperature, well width, doping, and capping were studied. Based on these results, resonant tunneling diodes (RTDs) and quantum well infrared photodetectors (QWIPs) were designed and are being developed. The THz spectral range offers promising applications for remote sensing for continuous monitoring of toxic agents and better security control at check-points.

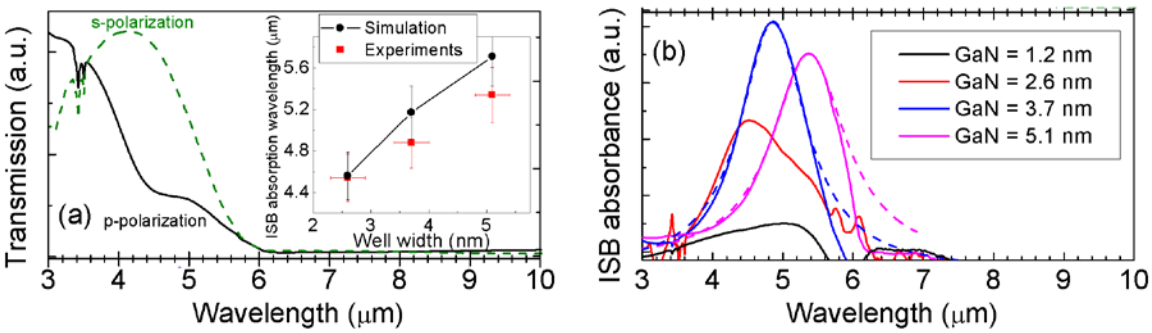


Figure 10. Left – p- (solid line) and s- (dashed line) transmission for MOCVD grown GaN/AlGaN structures with intersubband absorption (ISB) vs well width. Right – ISB absorbance vs wavelength for different well widths.

Voltage-Tunable High-Q Acoustic Resonators for RF Applications – Professor Robert York, University of California, Santa Barbara

Professor York and his research team have demonstrated significant improvements in the quality factor (q-factor or Q) of its novel voltage-switchable acoustic resonator technology using thin-film Barium Strontium Titanate (BST). The resonators show consistent low-loss performance for operating frequencies from DC to 40 GHz. The q-factor improvement was enabled by substituting tungsten and molybdenum in place of the original platinum layers in the acoustic Bragg reflector. These materials have lower acoustic losses and result in higher q-factors, which will ultimately improve the performance of reconfigurable RF filters using this technology. High-Q reconfigurable or frequency-agile filters can improve signal fidelity and enhance the operating bandwidth and range of RF communications devices, critical to many military systems. The next step in this work will be to make some minor adjustments in device design to incorporate the recent learning, and then demonstrate elementary frequency-agile transmission-based filter structures incorporating this new technology.

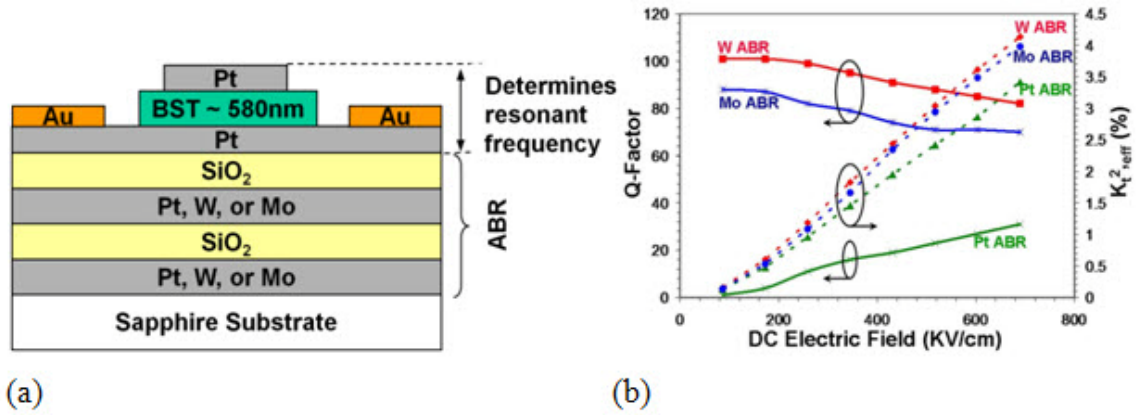


Figure 11. Voltage-tunable high quality factor acoustic resonator structure that can operate with low loss at microwave frequencies up to 40 GHz (a) and resonator performance versus tuning voltage (b)

Human Ears Inspired Microwave Passive Direction Finding – Professor Hao Xin, University of Arizona

This Short-Term Innovative Research (STIR) project will develop and demonstrate a microwave direction finding (DF) test framework including two antennas, a microwave scattering element, digital receiver circuitry and signal processing algorithms inspired by the human ear. Preliminary results have shown that the incorporation of the scattering element not only eliminates the phase ambiguity that plagues conventional two-antenna DF arrays, but also increases the general sensitivity of the system. The current prototype is capable of determining the direction of arrival (DOA) of a microwave signal to within two degrees with a system occupying a volume smaller than a cube one-half wavelength on a side.

The STIR also supported the design and construction of a portable RF direction finding test bed including two antennas, a human head-like scatterer, a digital receiver, and signal processing hardware with an initial implementation of the DOA algorithms. This portable test bed will be used in the near future to further study and develop novel RF direction finding techniques inspired by the amazing human auditory system including the cocktail party effects, the environment learning techniques, etc.

If the research is successful it will enable a significant reduction in the volume of antenna arrays for radio frequency direction finding, allowing high accuracy vehicle-mounted or even man-portable DF systems to operate in the HF to UHF bands, where the capability previously did not exist or was limited to systems with very large antenna apertures.

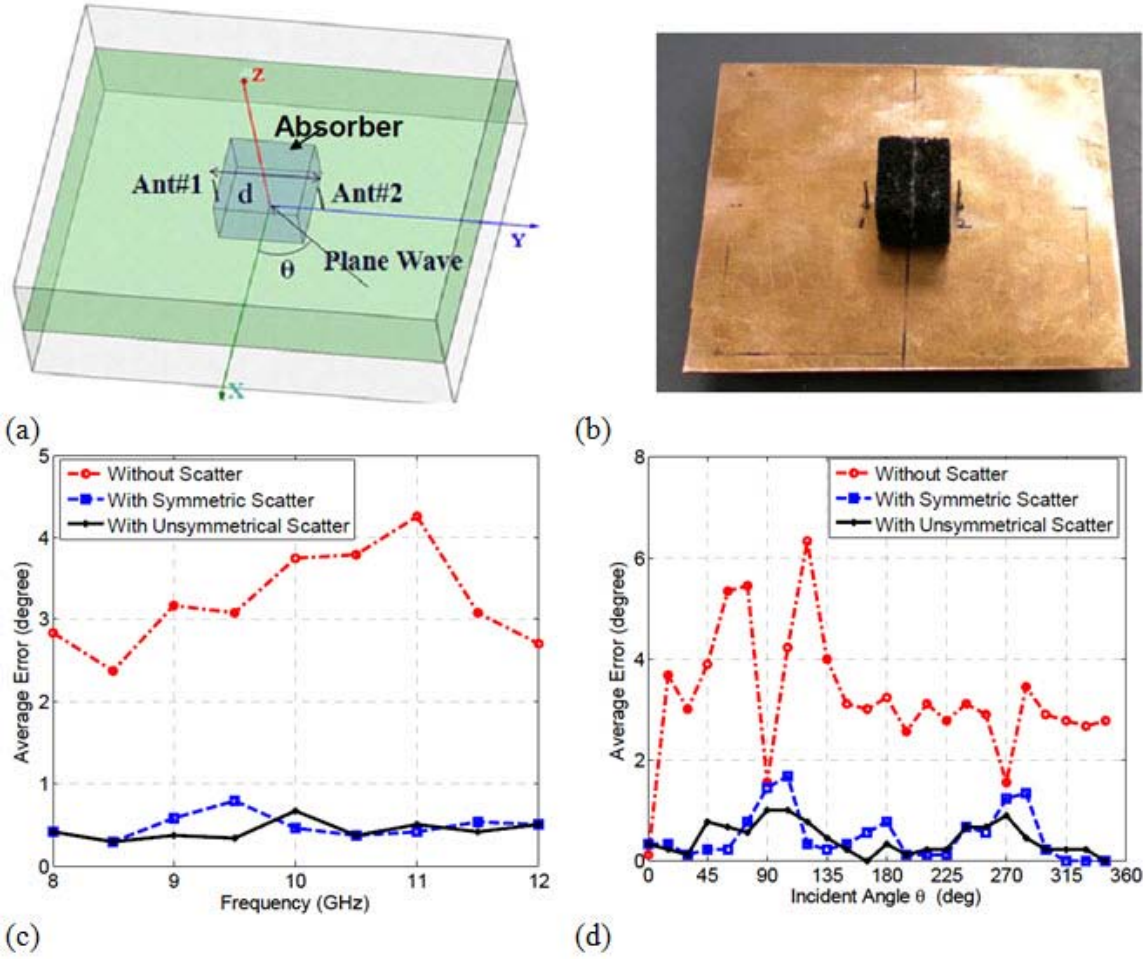


Figure 12. (a) A finite-element model illustrating the geometry of the two antenna and scatterer system with an incoming signal from an azimuth angle •. (b) The prototype X-band system with two-monopole antennas arranged around the scatterer. Measured average DOA estimation errors versus frequency showing significant improvement using the prototype system (c) averaged over all incident angles from 0 to 360 degrees with a 15 degree step angle) and incident angle (d) averaged over all frequencies from 8 to 12 GHz with a 0.5 GHz frequency step.

Monolithic Quartz Resonators for Infrared Detection – Dr. Srinivas Tadigadapa, Pennsylvania State University

It is well known that shear-mode quartz resonators made from certain crystal cuts can be used as very sensitive temperature sensors due to the high precision of frequency counting techniques. Professor Tadigadapa seeks to use this precision to demonstrate a highly sensitive infrared detector for imaging. The bottleneck to previous attempts has been the small sizes needed for a practical detector and the lack of an electronic circuit to read out the signal. However, the improvement in micro-machining technology has now advanced to the point that the feasibility of this idea can be tested in a reasonable (small) sized device. In the past year, Professor Tadigadapa fabricated and characterized quartz

resonators at 89 MHz and 235 MHz. At 500 microns these are still too large but the fabrication process appears capable of producing 50 micron pitch pixels. In addition, a simple Pierce oscillator readout circuit was tested and the results appear extremely promising to reduce the circuit complexity.

Integrated Sensing Using DNA Nanoarchitectures – Professor Michael Norton; Marshall University

There has been significant demonstrations in the area of DNA-based nanofabrication that is simultaneously exploring a variety of different DNA motifs in the context of the design requirements for both the 2-D and 3-D nanoelectronic architectures. Here, some of the underlying requirements for meeting the future goals include: increasing the microscopic structural periodicity to admit the entry of optical (and perhaps longer wavelength) excitation signals ; defining designer structures that amenable to the inclusion of functional molecules; and producing sufficiently large structural architectures (i.e., approaching or exceeding 1 mm) needed for the long wavelength characterization and testing. Some very important recent work on developing molecular lithography on origami at the intermediate scale (i.e., 10 nm to micrometers) is illustrated below. First, a new sequence design was achieved that extends away the DNA staples at the aperatures in rectangular origami (first illustration) and this is important because it allows for placing a single-strand DNA stretched across an aperture. Second, a bio-system was synthesized that associates two photoactive, green fluorescent protein (GFP) molecules with an oval shaped origami (second illustration) and this is important for achieving functionalized sensing devices.

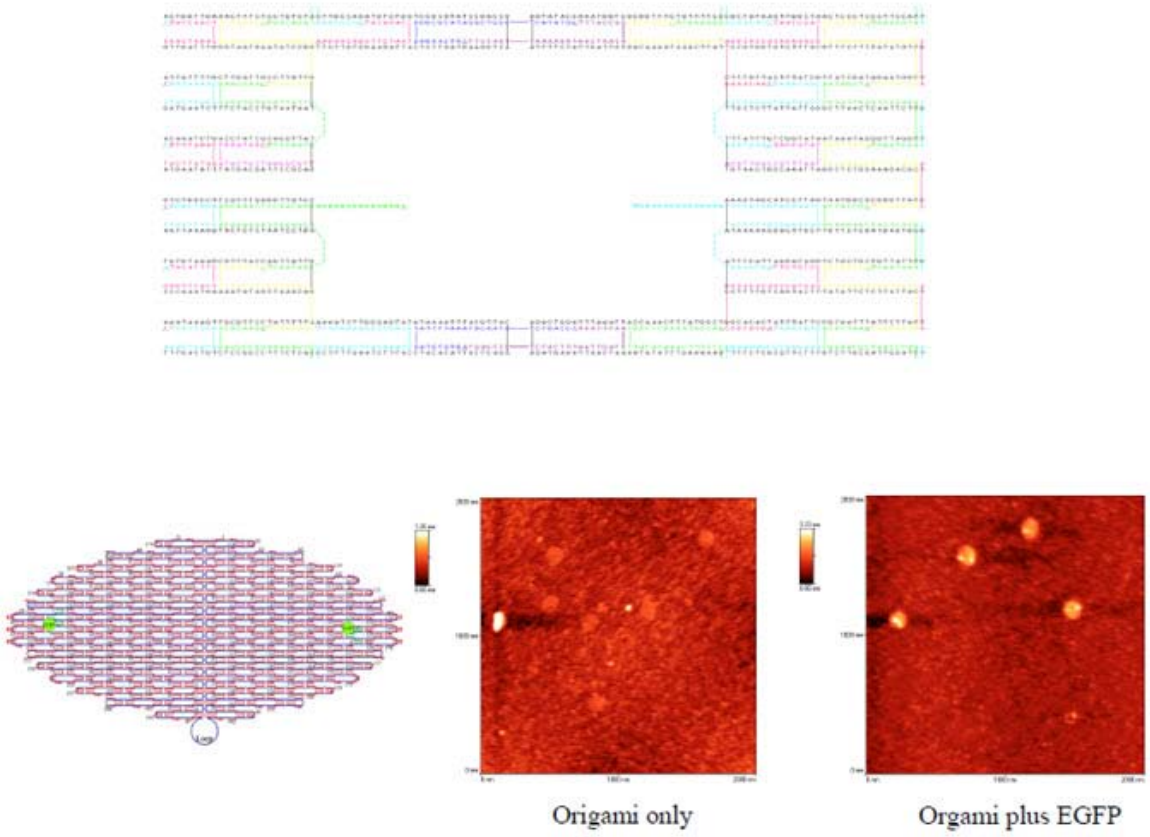


Figure 13. (Top) Rectangular Origami with Extended Staple Contacts; (Bottom) Oval Shaped Origami Design with two Photoactive, Green Fluorescent Protein (GFP) Molecules attached (on Left) and Synthesized Molecules with (Middle) and without (Right) Fluorescent Molecules.

V. TECHNOLOGY TRANSFER

The Electronics Division strongly believes its contract research program must serve the needs of the Army. To accomplish this objective, the Division strives to maintain the highest quality research contracts in the country and to optimize the interaction between Army laboratory programs and the Electronics Division contractor. Among the methods used are the evaluation of every division research contract proposal by Army scientists, the personal interaction and visitation of division technical monitors with laboratory scientists, and the conduct of special seminars, symposiums, and workshops for the benefit of Army in-house researchers. The result of these efforts is the transfer of basic research accomplishments into exploratory development performed at Army laboratories and the establishment of cooperative programs between Army laboratories and ARO Electronics Division contractors. Examples of these technology transfer and cooperative programs follow.

High Throughput Processing for Hyperspectral Imaging Sensors – Dr. Christopher Gittens, Physical Sciences Incorporated

Dr. Gittens recently induced a major change in the technology paradigm for hyperspectral infrared imaging while executing an ARO Phase I SBIR project. Specifically, the Phase I effort considered both "front end" and "back end" data processing for enhancing "target absent/target present" decisions for spectral images. Here, the benchmarking work (i.e., as specified by the SBIR Phase I Topic) utilized input data set characteristics for a TurboFTIR spectrometer which is an imaging Fourier-transform infrared (FTIR) spectrometer developed by D&P Instruments. However, the required data processing was also assessed in the context of PSI's Adaptive Infrared Imaging Spectroradiometer – Wide Area Detector (AIRIS-WAD) and this system was successfully demonstrated by PSI as the new leading candidate for insertion into the DoD Next Generation Chemical Standoff Technology program. At this time, PSI has engaged a Phase II and the chosen data processing hardware approach and imaging spectrometer technology have a very high probability of advancing the state-of-the-art and of becoming a component of the Next Generation Chemical Standoff Detection system that will be transitioned to JPM NBC Contamination Avoidance.

Infrared Spectroscopy in the Long Wave Infrared Regime – Professor Uwe Hommerich, Hampton University

Professor Hommerich has been collaborating Edgewood Chemical Biological Center on Laser-Induced Breakdown Spectroscopy (LIBS) in the mid-infrared (MIR) region between 2000 to 5750 nm. In their collaboration, the LIBS emission was measured from a variety of organic materials (paper, polyethylene, and PTFE) and inorganic materials (YAG crystal, quartz, glass, and aluminum), see Figure 14. No trace of thermal background emission and an excellent signal to noise ratio was observed. Nearly all previous LIBS experiments were limited to measurements in the ultraviolet (UV) to visible and near-infrared (NIR). However, molecules exhibit spectroscopic signatures in the MIR to far-infrared (FIR) wavelength region from vibrational and rotational transitions. Therefore, an extension of LIBS to the IR region promises to provide information which can augment results from conventional UV-VIS LIBS measurements. By adding the feature of laser energy control it can operate both as LIBS and Laser Induced Thermal Emission (LITE) technique/system. Recently, Brimrose Corporation was awarded a Phase I STTR contract to perform a detailed study of a LITE/LIBS system in the 1-12 μm range for potential applications in chemical, biological and explosive sensing. Professor Hommerich leads the research institution partnering with Brimrose in this effort.

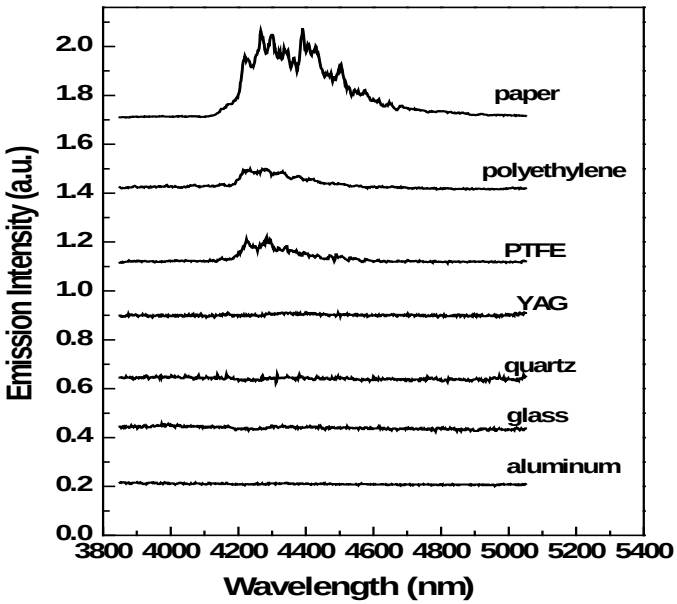


Figure 14. Mid-IR LIBS emission spectra of a series of organic materials: paper, polyethylene, and PTFE (Teflon); and inorganic materials: YAG crystal, quartz, glass, and aluminum.

Alignment Tolerant Optical Interconnects – SBIR Transitions to Missile Platform Development - Ultra Communications, Inc., Dr. Charles Kuznia, Vista, CA

Progress in work on alignment tolerant optical interconnects in a Phase II SBIR contract at Ultra Communications led to a recent Phase II enhancement award by Army PM SBIR. This enhancement award will continue the development efforts for 23 months to ensure transition of the technology to Army missile systems for enhanced interboard communications. Tests at Picatinny Arsenal in February resulted in a clear demonstration of the tolerance of the interconnects to high acceleration environments. This interconnect technology is based on vertical cavity surface emitting lasers (or VCSELs) technology developed with Army Research Laboratory from their free-space optical interconnect program. Peregrine Semiconductor (which spun-off Ultra Communications) developed a silicon-on-sapphire (S-O-S) circuit technology which ARL used in a flip-chip configuration to drive current through VCSELs. A patent ensued for this optical interconnect transmitter where light from the VCSEL emits through the transparent S-O-S circuitry. Ultra Communications furthered the patented work to make 2.5 Gb/s transceivers used in this SBIR for interboard communications. Optical vias were developed between the transceivers which allow transmission through PC board stacks up to 6 boards away. Drs. Gerhold and Liu of ARO and SEDD went to PEO Missiles & Space to demo of the technology with Ultra Communications which brought an endorsement by the Commanding General Genaro J. Dellarocco which led to the phase II enhancement. Collaborative efforts with Mr. Jeff Supp of Raytheon Missile Systems are underway to continue the development for future Army missile system needs.

Detection of Light Vehicles using Acoustic-to-Seismic Coupling – Professor James Sabatier, University of Mississippi

Heavy vehicles, such as tanks or other armored vehicles, can typically be detected using seismic and acoustic sensors to detect low-frequency engine noise; light vehicles are harder to detect, particularly in high noise areas. The objective of this research effort was to expand the techniques developed under the Human Signatures MURI to the detection of light vehicles. It was found that vehicle engines and tires generated broadband sound signals from low frequencies up to ultrasonic frequencies. Ultrasonic sound signals from moving light vehicles were detected in joint field tests with ARDEC and SEDD using a narrow band ultrasonic microphone. The magnitude of these signals showed dependence on the vehicle type. This research shows promise for the extension of these technologies to detect both humans and light vehicles under field conditions. This research led to an invitation for Dr. Sabatier to organize a working group on human, light vehicles, and tunnel detection. The first meeting was held in Beltsville, MD, and included 12 international participants plus 37 other participants from academia, industry, and government. Dr. Sabatier was also selected for an IPA assignment at SEDD to expand this research.

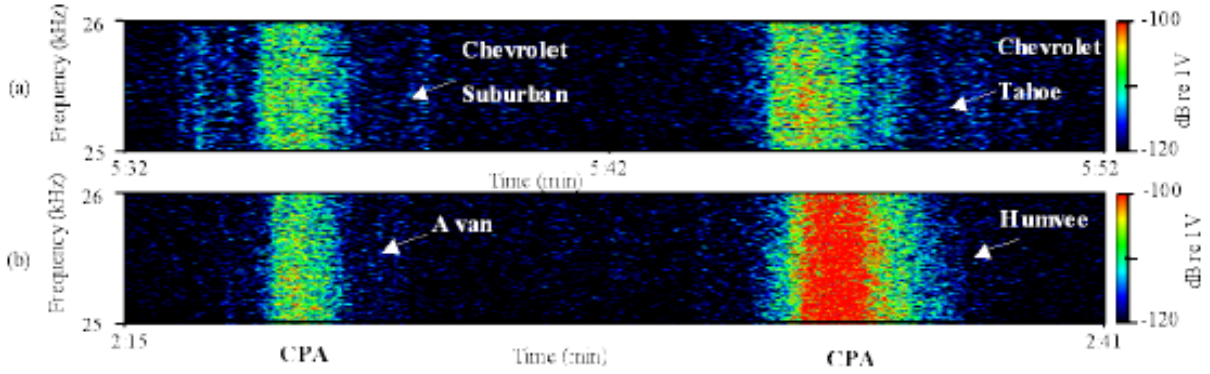


Figure 15. Spectrograms of the ultrasonic signals from vehicles moving on gravel road. (a) Two SUVs at 15 mph (Chevrolet Suburban and Chevrolet Tahoe), (b) A van and a Humvee at 20 mph.

Field/Circuit Computational Modeling and Simulation Software Tool – Professor Michael Steer, North Carolina State University; Dr. Christopher Penney, Remcom, Inc.

The goal of this Small Business Innovative Research (SBIR) effort was to combine existing circuit modeling tools and electromagnetic field simulation tools to create an integrated software program that will simultaneously model the circuits of radio transceivers including active and passive devices and the electromagnetic fields radiated by the radio antenna. The resulting hybrid field/circuit solver will permit a more comprehensive simulation of complex radio and sensor systems, and give insight to the user of the impact of the circuitry on the radiated fields and the effects of the external fields on the circuitry. Professor Steer and Dr. Penney integrated the fREEDA circuit simulator, which has been developed at North Carolina State University using Army basic research funding, with Remcom's XFdtd, a commercial finite difference time

domain electromagnetic solver. In Phase I of the SBIR, the team demonstrated remarkably accurate results for several test problems, including a complex radio transceiver attached to a monopole antenna. Successful execution of the project will enable a significant reduction in the design cycle time for Army mobile wireless communications systems through accurate prediction of radio system performance including antenna effects. The technology is expected to bring similar benefit to system development for applications in commercial wireless networking and communications.

VI. DIVISION STAFF

Dr. William Clark, Division Chief
Program Manager, Novel Electronic Devices

Dr. Michael Gerhold
Program Manager, Optoelectronics

Dr. Dev Palmer
Program Manager, Electromagnetics and RF Circuit Integration, and Power Electronics

Dr. Dwight Woolard
Program Manager, Solid State and High Frequency Electronics

Dr. John Zavada
Program Manager, Quantum Electro-Magnetic Devices

I. PROGRAM OBJECTIVES

The Army must be mobile to operate and perform effectively in operational theaters from equatorial to polar latitudes, an enormous variety of environments, terrain, and weather conditions. Army doctrine requires that commanders know their environmental and the digital battlefield requires detailed and sophisticated information concerning distributed terrain features and conditions.

The Army's primary interest in the atmospheric and terrestrial sciences ranges from the near subsurface into the lower atmosphere. As a result, the research need in the environmental sciences stems from the impact that the environment has upon virtually all aspects of Army activities. Despite continuing efforts to develop an all-weather/all-terrain capability, environmental conditions still constrain Army operations. At present, the Army cannot rapidly and efficiently perform the terrain analysis that is required before vehicles and weapons systems can be effectively deployed. The potential impact and leverage of environmental factors must be clearly understood in order to increase existing system capabilities and performance, take advantage of environmental weakness of adversary systems, and optimize the design of new systems. As military technology becomes ever more complex and sophisticated, both systems and operations are increasingly influenced by the variability in natural environmental conditions. Sensor and weapon system developers also must understand environmental effects on system performance to optimize design effectiveness. A capability to remotely sense and interpret the features of the Earth's surface, both natural and anthropogenic, and an automated capability/methodology for the handling and analysis of large aggregates of remotely sensed data are critical requirements for the twenty-first century Army. A continuous dynamic interaction takes place between solid earth materials and the most abundant fluids, water, and air.

One long-term goal of the Environmental Sciences research effort at the Army Research Office (ARO), which ties together the individual research efforts within the Atmospheric Sciences Program and the Terrestrial Sciences Program, is the integration of meteorology, hydrology, and geomorphology. In particular, there is a need for the development of first-principle physical/chemical processes models, better technologies and methodologies for environmental characterization and prediction, and computer-based techniques for monitoring, modeling, and simulating the natural environment. Special emphasis is given to the need to better understand, model/simulate, and predict those environments/conditions that are most dynamic or restrictive to systems performance or military operations.

At the same time, the Department of Defense and particularly the United States Army increasingly recognizes that the capability to establish and provide base operations to support operational forces requires a new examination of the immediate environment surrounding the soldier. As a first step, the Army established an Integrated Capabilities Development Team (ICDT) to identify the Army’s required capabilities for contingency land basing/Army base camps. As a result, Commanding General, MANSCEN released a draft Concept Capability Plan titled, Camps for the Future Modular Force (2015-2024).

It is likely that DOTMLPF engagement will result in a focus on improving specific capabilities or overcoming identified technology barriers. This outcome would, in turn, result in a call for needs driven basic research. The Environmental Sciences Division is, therefore, engaged in a basic research needs analysis to support the potential needs of military habitation science.

II. RESEARCH PROGRAM

A. General Information

The overarching objective of Environmental Sciences basic research is to enable the Army to train, plan, and operate effectively in all environments by improving fundamental understanding of terrain, land-based, and lower atmospheric phenomena. The Army Terrestrial and Atmospheric Sciences basic research program addresses the broad spectrum of terrain, land-based, and lower atmospheric phenomena that affect the Army – from home station to its deployment and sustain operations throughout the world.

Because the natural environment is, by nature, a highly complex and dynamic system characterized by complicated feedbacks, there is an increasing need for multidisciplinary approaches to address the multifaceted problems that are addressed by the ARO Terrestrial Sciences basic research program. This extramural research program is developed in conjunction with the laboratories of the USACE Engineer Research and Development Center, the Countermine Division of the US Army CERDC Night Vision and Electronic Sensors Directorate and the Army Engineer School, with input from land managers at several Army installations. It is also coordinated with related programs in other Department of Defense and US government agencies. The core funding of the Terrestrial Sciences Program comes from the Army Research Office. Other funding sources are sought both within and outside the Army. Together, this coordination and leveraging in areas of common interest brings more Terrestrial Sciences research and new knowledge and capability to the Army than would otherwise be the case.

In the same vein, the Army has the responsibility to provide fundamental knowledge of the atmospheric boundary layer over land (the continental boundary layer, CoBL) to all U.S. armed services since that boundary layer is the primary theater for Army operations. Intelligence preparation of the battlefield depends on a full knowledge of atmospheric conditions and their effects on operations, weapon systems, and the soldier. It requires an ability to estimate atmospheric details at specific locations and a future time to maximize strategic weather advantages. Knowledge of the atmosphere and its effects on soldiers and sensor systems are essential for command and control as well as visualization of the battlefield at all echelons. The Army lead for chemical and biological defense requires detailed knowledge of the threat once it is induced into the air. In garrison, Army training and preparedness depend on accurate representation of atmospheric test conditions and on physically correct portrayal of atmospheric processes and effects in simulations.

B. Thrusts and Trends/Workpackages

Terrain affects all aspects of military operations. The effective understanding and use of terrain is critical to military success on the battlefield. It is in effect a force multiplier, affecting mission planning, system performance, unit mobility and effectiveness, and training readiness. At present, the Army cannot rapidly and efficiently perform the terrain analysis that is required before vehicles and weapons can be deployed. A capability to remotely sense and interpret the features of and upon the earth's surface, and an automated capability/methodology for handling and analysis of large aggregates of remotely sensed data are critical for the 21st Century Army. Terrain data consists of information about land surface elevation (i.e., topography), ground character information, natural terrestrial features and attributes, man-made targets, and both natural and urban environments.

Research in **Terrain Properties and Characterization** is aimed at the understanding and effective use of terrain for soldier and system success. Accurate assessment and characterization of terrain data in near real-time is a high-priority research issue. Research related to terrain properties characterization is directed toward two general issues: (i) fostering the development of advanced geoscience capabilities for the rapid post-acquisition generation, analysis, and utilization of terrain information acquired through remote sensing approaches; and (ii) the enhancement of current geophysical and geochemical sensing techniques of interest to the Army and the development of new sensor technologies, particularly that to address the high priority problem of explosive device detection. Understanding the physical character of the top half-meter of soil at both the micro- (c. 5 cm) and macro- (c. 10 m) scale is essential for the detection, identification, and neutralization of different types of buried explosive devices. Progress in sensor technology and sensor signal processing and discrimination requires a fundamental understanding of environmental effects. An ability to estimate macro-scale soil characteristics over larger areas worldwide is needed to guide the operational deployment and optimization of mine detection and neutralization assets. Currently, such soil character knowledge and capability to estimate the required soil physical properties over large spatial areas in real-time do not exist.

Research in **Terrestrial Processes and Dynamics** is oriented towards the development of an improved understanding of surficial processes within the different and varied terrestrial environments that can affect Army operations. Such processes typically are complex and difficult to quantify because they frequently are governed by the nonlinear dynamics that are an intrinsic feature of physical (and biologic) processes. The interaction of Earth surface processes with the ambient landscape operate over a wide range of often-discontinuous time and space scales. Explicit consideration of these processes and their interactions will lead to critically-needed improvements in the ability to predict both the effects of the ambient environment on Army operations and the impact of Army activities on the natural environment. The primary objectives of efforts to characterize the natural environment and understand terrestrial processes are to better prepare the soldier for combat and to contribute to the next generation of battlefield and

land management decision aids. An important application of this research is to develop or enhance integrated system models and simulators.

Research in the area of **Terrestrial System Analysis and Modeling** is aimed towards enhancing current Army numerical modeling and simulation capabilities for the surface and near-surface environments. These efforts typically are directed toward mobility analysis, the prediction of watershed response and/or groundwater flow and transport to changing input or boundary conditions, the analysis of specific military engineering activities, and prediction of the environmental response to military testing and training activities.

The atmospheric sciences research portfolio is broadly based to address the wide spectrum of conditions and influences of the atmospheric boundary layer on Army operations and systems. It is divided into three general research areas of the boundary layer problems:

- Battlefield Sensing Exploitation: Observations, fusion, and forecasts of meteorological parameters in complex environments.

- Weather Exploitation: Atmospheric Effects on Performance of Soldiers and Systems: Quantification, Uncertainty, and Risk

- Virtual Atmospheric Effects Test bed: High-Resolution Simulation of the Atmosphere and Signal Propagation

Synopses of these research areas follow:

Battlefield Sensing Exploitation: Observations, fusion, and forecasts of meteorological parameters in complex environments – Army operations occur at a finer spatial scale and tempo (the "soldier scale") than can be met with the current generation of operational weather forecast models. Atmospheric data at the soldier scale in the CoBL is essential for the diagnosis of current battlespace weather and for short term forecast/extrapolation of local conditions. Forecast models provide broad, non-specific guidance. In-situ data are essential for research development and effective operations.

The Army must have a capability to capitalize on the existing data sources – winds aloft as measured by aircraft, near-ground temperature and moisture sensors which are not used; atmospheric effects on EM or acoustic propagation may be used to infer atmospheric states; measured atmospheric states can infer propagation performance. Data from non-conventional sensors l – incorporated in UAS/ UGS systems or in soldiers' equipment – must be developed, and used routinely before deployment to the field. New, low-cost, sensors for probing the four-dimensional structure of the CoBL are needed. Atmospheric data becomes spatially and temporally distributed - from fixed or mobile platforms. Robust techniques will be required to assimilate those disparate data

into a comprehensive analysis, supporting the entire spectrum of Army weather information.

Research is needed to develop and demonstrate a capability to better characterize and predict the complex environment in which the current and future force will fight (including urban terrain, complex topography, forest canopies and jungles). Solutions are sought through the exploitation of new analysis techniques, novel sensor technologies and the fusion of information from multiple disparate conventional and unconventional sources of meteorological data.

Weather Exploitation: Atmospheric Effects on Performance of Soldiers and Systems: Quantification, Uncertainty, and Risk – The Army transformation has committed the Army to relying extensively on advanced communication networks and sensor systems. Visibility (see-ability) across the EM spectrum is impacted by absorption and scattering by the air and its contents. Scintillation becomes a more significant, uncontrolled problem as detectors become more sensitive. Remote sensing of atmospheric properties - wind, temperature, humidity, aerosols, or chemicals – depends upon propagation properties of the atmosphere. Hot, cold, wet, dry conditions stress the body and capabilities. A sniper in a sweltering attic may not be able to perform a mission. Zones of enhanced or inhibited acoustic detection change with atmospheric structure. Every operation has an operations plan with an intelligence preparation of the battlefield – with weather conditions and effects being a vital part. Mission planning, armament selection, sustainability of contact all depend upon current or forecast atmospheric (weather) conditions. Achieving and maintaining battlespace awareness and superiority requires a comprehensive understanding of the weather and weather effects.

The Army depends on atmospheric observations and forecasts for specific locations and times to select appropriate strategies, use the systems giving superiority, through forecast-based tactical decision aids. As the Army transformation emphasizes small unit operations and rapid communications among them, knowledge of the unit local weather conditions and potential to explore the conditions become increasingly important. As the Soldier presently has a distinct operational advantage in nighttime conditions, understanding the effects of the nocturnal (stable) boundary layer is particularly important. Adjacent to the ground, conditions often seem benign, but in these conditions the lateral circulations are strongly affected by subtle terrain differences and complex vertical structures that are rarely known or measured. Capabilities for exploring weather and terrain conditions such as “quiet” corridors for UAS surveillance of borders, mountain passes, or IED activity should be developed.

Virtual Atmospheric Effects Test bed: High-Resolution Simulation of the Atmosphere and Signal Propagation – Dynamic atmospheric simulations at resolutions as fine as 1 m may be required to investigate the complex interactions in the atmosphere and with the land surface. Capabilities for accurate calculations in complex terrain and nonstationary atmospheric boundary layers that are nearly indistinguishable from real-world data. Use atmospheric fields from these simulations as inputs to similarly high-resolution codes for acoustic and electromagnetic wave propagation and for

transportation and diffusion of aerosol CBRN agents. Simulate atmospheric effects on battlefield sensors and RF communication networks including both ground and air-based nodes. Utilize DoD high-performance computing capabilities to provide maximum possible resolution and fidelity.

C. Research Investment

The FY09 allocation of Army basic research funds for the Terrestrial Sciences core program from the Army Research Office was just over $1M and an additional $2.9M was received as the result of competitive success in a variety of Department of Defense (DoD) and Army funding programs including the DoD Presidential Early Career Award for Scientists and Engineers (PECASE) Program, Defense Experimental Program to Stimulate Competitive Research (DEPSCoR), Defense University Research Instrumentation Program (DURIP), DoD Strategic Environmental Research and Development Program (SERDP) and Environmental Security Technology Certification Program (ESTCP) and Army Historically Black Colleges and Universities/Minority Institutions (HBCU/MI) and Tribal Colleges and Universities program for research and/or infrastructure initiatives plus the Small Business Innovative Research (STIR)/Small Business Technology Transfer (STTR) Programs. Customer funding of $5.5M came from DARPA, SERDP/ESTCP, the RDECOM Armaments Research and Development Center, Army PM Close Combat Support, the CERDC Night Vision and Electronic Sensors Directorate Countermine Division, five laboratories of the USACE Engineer Research and Development Center, the Army Research Laboratory Weapons and Materials Research Directorate, and two Army and Marine Corps installations. Finally, an additional $1.9M was received for a Congressionally-directed research initiative.

For FY09, a total of $1.5M was executed to support research programs in the Atmospheric Sciences area. The Army's Defense Research Science basic research funds represented the lion's share of the program. $0.5M was executed on studies of atmospheric dynamics and the balance was spent on studies of remote sensing of the atmospheric boundary layer. Supplemental funding using funds from outside ARO funds supported basic research in stable boundary layers. Current planning for FY10 indicates an expenditure of about $1.4M in this area.

Military Habitation Science research activities were on the order of $4.9M with the majority of the spending, $4.3M executed in cooperation of the Defense Advanced Projects Agency (DARPA) for the Materials with Novel Transport Properties (MANTRA) effort to develop novel membranes for water treatment. The Army's Defense Research Science basic research funds contribution was $0.2M with the balance coming from other Army sources.

D. Principal Investigator Interactions

Researchers from Duke University (L. Carin and L. Collins), Georgia Institute of Technology (W. Scott), the University of Florida (P. Gader), the University of Missouri-

Columbia (J. Keller and D. Ho), and the University of Louisville (H. Frigui) have been collaborating with the Army PM Close Combat Support and the Countermine Program of the CERDC Night Vision and Electronic Sensors Directorate in the development of new and improved technical approaches, sensor modeling capabilities, and signal processing-sensor fusion algorithms for handheld, vehicle, robotically-deployed, and airborne landmine detection technologies. Substantial technology transfer occurred from these focused research activities over the past year.

Other Terrestrial Sciences program Principal Investigators have been collaborating or directly interacting with one or more of the USACE-ERDC laboratories during the course of their ARO projects. For example, J. Baggett (University of Wisconsin La Crosse) is undertaking the research necessary to develop and implement improved algorithms for groundwater flow model calibration; T. Illangasekare (Colorado School of Mines) is conducting medium-scale tank experiments to develop systematic approaches to the calibration of numerical modeling approaches used to simulate groundwater flow and transport in environmental restoration of present military installations and formerly-used defense sites contaminated by non-aqueous phase liquids in work of high interest to the Coastal and Hydraulics Laboratory; Waymond Scott (Georgia Institute of Technology) is developing a physical model for electromagnetic and ground penetrating radar sensors.

E. McDonald and colleagues at the Desert Research Institute are working with the Natural Environments Test Office at US Army Yuma Proving Ground to develop an integrated, predictive numerical model for forecasting terrain conditions and surface responses at different scales in desert regions to support military tactical operations, testing and training, P. Rundel of the University of California of Los Angeles, J. Juvik of the University of Hawaii-Hilo, and K. Nagy of the University of California at Los Angeles are conducting research related to the management of threatened and endangered animal and plant species on the US Army National Training Center and USMC Air Ground Combat Center; T. Bullard of the Desert Research Institute is conducting geomorphological research at the Naval Surface Warfare Center in Port Hueneme, CA.

Redlands Institute of the University of Redlands supported a national strategic planning workshop hosted by the US Institute for Environmental Conflict Resolution. ARO PI J. Henk, Redlands Institute Director served on the workshop steering committee, and technical staff from the Redlands Institute applied Geographic Information Science (GIS) research knowledge and technical capacity obtained under ARO funding to develop an on-line demonstration portal intended to improve access to innovative technologies that may enhance decision making by DOD and other federal land managers.

At the recommendation of the Army Yuma Proving Ground Natural Environments Test Office (YPG-NETO), ARO PI Eric McDonald of the Desert Research Institute (DRI) provided an analysis of soil and terrain conditions in Afghanistan, with comparisons to Iraq and analogs at Yuma Proving Ground to Dr. J. J. Streilein, Technical Director of the Army Test and Evaluation Command. This analysis was conducted to support current considerations for mobility testing of the Mine Resistant Ambush Protected (MRAP) vehicles for deployment to Afghanistan. Conducted by DRI under the auspices of its

current grant from the Army Research Office, this analysis was based upon few soil samples from Afghanistan and expert-based image terrain analysis that integrated satellite and remote sensing imagery and morphometric assessment of landforms using a digital elevation model coupled to a geographic information system. This DRI analysis concluded that terrain common to Afghanistan is likely to pose a severe challenge to MRAP mobility, due to large areas of landforms characterized as 'mountain highlands'. Four test courses at YPG were recommended as the best analogs for terrain conditions most likely to be encountered in Afghanistan. Detailed analysis of the soil and terrain conditions associated with each course, along with how each course provides terrain analogs for key countries within the CENTCOM area of responsibility, has been provided in a report that DRI prepared for YPG-NETO.

As a consequence of the 11 September 2001 terrorist attacks on the United States, researchers who study social networks have created sophisticated new programs to probe beneath the surface of social interactions and recently have begun to apply this research to counterterrorism. The research ARO Terrestrial Sciences PI Kathleen Carley, a computer scientist at Carnegie Mellon University, was cited in the news article "Counterterrorism's New Tool: 'Metanetwork' Analysis" in the 24 July 2009 issue of the prestigious journal *Science.* Dr. Carley's CMU research team has developed the new technique of "dynamic metanetwork analysis" which can be used to understand dynamic change in terrorist networks over time. Whereas classic social network analysis deals only with the question of "who" in networks, the new CMU "metanetwork" approach includes the "who, when, what, where, and why." The CMU "Organizational Risk Analyzer" (ORA) allows analysts to use information about people to "connect the dots" and the program then uses both network theory and social psychology to examine the social network and finds those people, who represent a threat to the overall system. In the case of a network of insurgents, an analyst can use the ORA to identify the people who are crucial for a network's survival. Dr. Carley and MAJ I. McCulloch of the US Military Academy have used the 'metanetwork' analysis approach to analyze 1500 videos made by insurgents in Iraq, construct a network, and then generate forensic clues that identify the critical people in some of the insurgent cells. Carley and McCulloch also have worked with the U.S. military to "operationalize" the technique in Iraq, where U.S. commanders there are faced with too much information and too little time to act on it. The CMU 'metanetwork' software produces clues and patterns, boosting the chances of stopping insurgents.

Several Terrestrial Sciences researchers received awards and citations during FY 2009. Dr. Stephen Elgar, a senior scientist at the Woods Hole Oceanographic Institute has been selected as one of eight National Security Science and Engineering Fellows for 2009. Dr. Elgar, who was funded by the ARL/ARO Terrestrial Sciences program from 1999-2006 to study nearshore sediment transport and onshore sandbar migration, will receive significant research funding for five years to conduct unclassified basic research on topic of DOD interest and also will serve as a science advisor to the Office of the Secretary of Defense. Dr. Enrique R. Vivoni of New Mexico Institute of Technology, a PI in the ARO Terrestrial Sciences Program and a recipient of an ARO PECASE award for 2008, was named a U.S. Fulbright Scholar for 2009 to perform research entitled: "US-Mexico

Studies on Ecohydrological Interactions during the North American Monsoon". The award provides support for an extended 6-month stay at the Universidad de Sonora in Hermosillo, Sonora, Mexico during the spring 2009 period. Professor Vivoni research will be focused on combining remote sensing, field observations and numerical modeling of summer season hydrological phenomenon in the North American Monsoon region, extending from the southwestern U.S. into western Mexico. ARL/ARO Terrestrial Sciences PI Professor Rafael Bras, Distinguished Professor of Civil and Environmental Engineering and Dean of the Henry Samuli School of Engineering at the University of California Irvine, was inducted into the Puerto Rico Academy of Sciences on 15 July 2009.

Dr. James Sabatier a distinguished researcher in the National Center for Acoustics Research at the University of Mississippi funded by the ARO Terrestrial Sciences program has accepted an IPA position in ARL-SEDD. In this capacity, Dr. Sabatier will support the ARL mission in the areas of geophysical sensing phenomonologies and sensor fusion, with a specific focus on the multi-modal signatures of personnel sensing mechanisms that are needed to advance the implementation of novel algorithms for detection and classification. Additionally, Dr. Sabatier will apply his technical expertise in both passive and active non-imaging and imaging sensors, multiple sensor target signatures, signal processing methodologies, data fusion methodologies for Intelligence, Surveillance, and Recognition applications.

Similarly, the Atmospheric Sciences Program is closely coordinated with research and development programs in the Battlefield Environments Division of the Army Research Laboratory. Interaction with Army scientists and engineers occurs through personal contact in program reviews, planning meetings, seminars, and joint workshops. Both ARL and ARO activities are coordinated for the DTRA stable boundary layer initiative. ARO developments with new turbulence closure is shared with BED scientists in modeling and observational studies of diurnal changes in the Owens Valley. Doppler wind lidar analyses in the valley provide a unique opportunity to evaluate models at high resolution. The program also interacts with the Army Test and Evaluation Command’s 4DWX (four-dimensional weather) program to support test ranges. The program is coordinated with other DOD programs through the Atmospheric and Space Sciences Scientific Planning Group; with professional societies through meetings, planning groups, and workshops; through participation in Joint Action Groups of the Office of the Federal Coordinator for Meteorology; and through participation and review of DoE, NOAA and NSF agency programs.

Boundary Layer Meteorology: Research thrusts with highest Army priority include the diurnal evolution of the boundary layer. A particular interest is very stable boundary layers, and the transitions of stability, which occur with sunrise and sunset. Recent reports from different agencies have identified a major gap in operational weather capabilities, with large uncertainties, at spatial scales of 20 km to 20 m due to a deficit in understanding processes at those scales. The science base of knowledge is sparse partly because of the lack of boundary layer observations at these scales. Furthermore there is a large disconnect between basic research and operational use because these scales are

poorly represented in forecast models. Activities are underway to improve integration of basic research, innovative measurements, test range capabilities, Army weather data suppliers, and the user community to attempt to bridge the knowledge and operational gap at scales most important to the soldier. The ARO research program will emphasize innovative analysis and interpretation of the data from all sources by its sponsored researchers.

Remote Sensing: Future research will give high priority to measurements of fields of wind, moisture, and temperature in the atmospheric boundary layer (ABL) at high time and space resolution. Although significant progress has been made through the development of high resolution scanning Doppler lidars, the ABL remains a very under measured and poorly characterized. New measurement technologies will be pursued for measurement of ABL turbulence, temperature and moisture. Unique mobile platforms will be pursued to provide wide coverage of ABL structure for emergency response, hazards monitoring and 24/7 resolution of ABL processes in all types of surface complexity.

Finally, nascent Military Habitation Science research activities are being closely coordinated with U.S. Army Research Laboratory's Sensors and Electron Devices Directorate (SEDD), U.S. Army Soldier Center (Natick), US Army Tank-Automotive Research, Development and Engineering Center (TARDEC), and the Engineer Research and Development Center (ERDC) is the US Army Corps of Engineers. In particular, the Environmental Sciences Division is focused on resource reuse. For example, effort by Dr. Brian Dempsey at The Pennsylvania State University examines potential improvement in forward operating base water utilization by examining the effects of in-line coagulation on removal of wastewater effluent organic matter (EfOM) and on fouling of polyethersulfone (PES) ultrafilters.

III. SPECIAL PROGRAMS

A. Presidential Early Career Award for Scientists and Engineers (PECASE) Program Awards

Predictive Modeling of Diffractive and Non-Diffractive Propagation in Forested Terrain – K. C. Slatton, University of Florida

K. C. was the recipient of an FY07 PECASE award and under this 5-year project is investigating new and effective ways to predict propagation of sensor signals in forests. This research addresses a critical Army need for new analytical methods to estimate visibility and propagation of microwave and acoustic signals in highly occluded environments. The approaches being developed are inherently generalizable to many different sensing and communication modalities because signal propagation over a wide range of diffraction regimes is being analyzed. The objective of this project is to develop a flexible information-theoretic framework, coupled with simplified physical models and high-resolution airborne laser ranging data, to predict diffractive and non-diffractive

propagation performance in forested terrain with measured uncertainty. Specific questions that will be answered include: (i) How does uncertainty in the estimated line-of-sight visibility evolve as a function of tree spacing, understory density, instantaneous field of view, and lidar point density?; (ii) How do measures of GPS performance, such as signal-to-noise ratio and time-to-first-fix, vary as a function of elevation above the forest floor and vertical distribution of canopy closure?; and (iii) How does the expected error in predicted attenuation behave as a function of forest floor surface morphology and tree spacing? Line-of-sight-visibility (LOSV) is perhaps the most important of all propagation regimes in highly occluded environments, such as forests. It is also, by definition, not diffractive at decimeter to meter scales. In order to achieve a large angular diversity of LOSV samples through the canopy and be able to validate it with rigorous ground truth parameters, including traditional stand-level descriptions of forests, the specific problem of estimating intercepted photosynthetically active radiation (IPAR) has been studied.

Scaling Properties and Spatial Interpolation of Soil Moisture – J. D. Niemann, Colorado State University

J. Niemann was the recipient of a FY04 PECASE award and over the past four years has been investigating the scaling properties and spatial interpolation of soil moisture. Soil moisture is an important issue in managing Army training lands, detecting land mines and unexploded ordnance, and determining troop and vehicle mobility in combat. Unfortunately, soil moisture is highly variable in space and time and is difficult to observe over large regions with an adequate level of resolution or detail. The primary objective of this project is to develop a method to estimate high resolution soil moisture patterns from in-situ and/or remotely-sensed soil moisture observations as well as high resolution topographic data.

A combined hydrologic- geomorphic model has been developed together with numerical tools to examine the dependence of soil moisture on topography. This model has been tested at the Fort Cobb experimental watershed, which has soil moisture observations available with excellent temporal resolution for about one year, and in the Illinois basin, which has a long-term soil moisture dataset for the past 26 years. An empirical orthogonal function analysis was used to decompose soil moisture patterns obtained from both remote-sensing and in-situ measurements. The most interesting results were obtained for the Tarrawarra catchment in New Zealand where the soil moisture patterns are highly dynamic. In this case, the most important spatial pattern underlying the soil moisture is highly correlated with the wetness-index (a topographic attribute), which can be derived from a steady-state description of lateral flow. The second most important pattern of variation resembles the potential solar radiation index (essentially another topographic attribute), which is related to evapotranspiration. The third most important pattern is most highly correlated with elevation and may describe the modification to the steady-state lateral flow pattern that occurs during transient periods.

Effects of Seasonal Land Surface Conditions on Hydrometeorological Dynamics in Southwestern North America – E. Vivoni, Arizona State University

Dr. Vivoni was the recipient of a FY08 PECASE award that will allow him to address knowledge current gaps about how the land surface in semiarid-arid regions interacts with and modulates a monsoonal system. Over the course of his PECASE research, he will undertake a set of comparative studies along the gradient of the North American Moonsoon System on four Army installations (Yuma Proving Grounds, Fort Huachuca, Fort Bliss and Fort Carson) that will characterize land surface conditions and determine their influence on monsoonal hydrological and atmospheric processes. Semiarid to arid landscapes dominated by monsoonal summer rainfall can have a dramatic seasonal greening that affects land-atmosphere interactions and rainfall-runoff dynamics. Little is known about these interactions in semiarid-arid monsoon regions throughout the world, primarily due to a paucity of ground observations and limitations in the remote sensing and numerical modeling of these complex systems. The research is organized into four activities: (i) deployment of high-density instrument networks and surveys during summer periods; (ii) synthesis, analysis, and evaluation of field observations and remote sensing data; (iii) modeling studies that integrate field and remotely-sensed data to analyze hydrometeorological processes; and (iv) regionalization efforts through cross-site comparisons and numerical simulations.

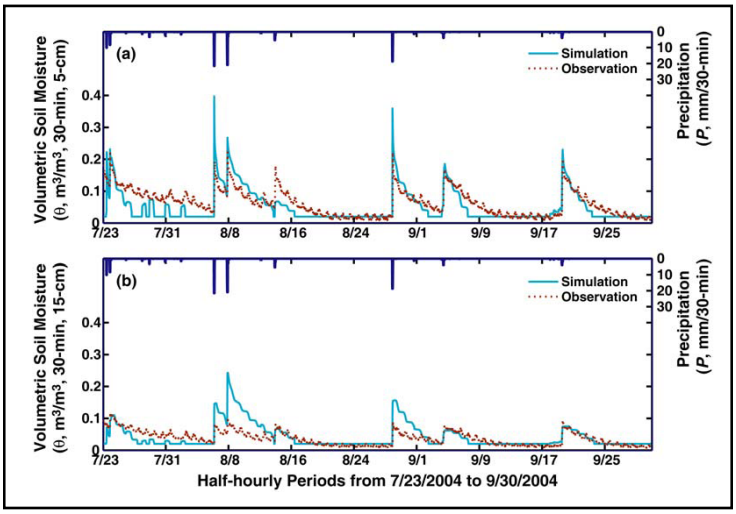


Figure 1. Comparisons of observed and simulated volumetric soil moisture (□□ in m3/m3) at the EC site. (a) Surface soil moisture at 5cm depth. (b) Top layer soil moisture at 15-cm depth. Data from a single sensor used in (a), while a weighted average of three sensors used in (b).

Numerical simulations are carried out in the two modeling domains using tRIBS, a fully-distributed, physically-based model of hydrologic processes. The model has a spatially-explicit treatment of basin heterogeneities in topography, soils, vegetation, and atmospheric forcing. A catchment is represented by a TIN consisting of elevation, channel and boundary nodes, which capture basin features with a reduced number of

elements. The model accounts for a range of hydrologic processes that track the catchment response, including: (1) canopy interception; (2) evapotranspiration from bare soil and vegetated surfaces; (3) infiltration and soil moisture redistribution; (4) shallow subsurface transport; and (5) overland and channel flow. Point-scale simulations at the EC site (Figure 1) were compared with soil moisture and energy flux observations during July 23 to September 30, 2004. Note the good match between the simulations and observations with respect to the wetting and drying sequence. The observed peak soil moisture is overestimated during brief periods, while the recession rates are too high during the early portions of the simulation. The model match improves with time with excellent correspondence for events in September at both sampling depths. Improvements occur in soil moisture peak values and recession characteristics. This indicates that inaccuracies in the assumed dry initial condition were dissipated or reduced during the simulation. Overall model performance, however, is considered to be reliable at the point-scale in terms of the soil moisture response to precipitation.

B. Defense University Research Instrumentation Program (DURIP) and Historically Black College and University/Minority Institution (HBCU/MI) Research Instrumentation Program

Raman-Enhanced Laser-Induced Breakdown Spectroscopy (LIBS) for the Rapid Detection and Evaluation of Biological Warfare Agents in Complex Environments – Lewis Johnson, Florida A&M University

There is an increasing interest on the part of the military and homeland defense organizations in technologies that have the potential for the real-time detection and identification of hazardous and toxic materials like explosives and chemical-biological agents. In this research FY06 project, laser-induced breakdown spectroscopy (LIBS) is being coupled with ultraviolet resonance Raman spectroscopy (URRS) to enhance species selectivity for the rapid detection of biological warfare pathogens and toxins under both laboratory and field conditions. LIBS plasma phenomena in various regimes are being studied to identify ways to extend plasma lifetime and in effect improve LIBS sensitivity, the optimal parameters which enable the elemental profile to differentiate various biological pathogens will be identified, a LIBS system is being developed to detect pathogens in the water-diluted liquid phase, and a combined LIBS/RAMAN system will be developed to detect biological agents in complex environments.

Economical Three-Dimensional Interrogation of Complex Flows near the Surface and their Transport – Dr. Christoph Thomas, Oregon State University

Dr. Christoph Thomas and Dr. Larry Mahrt of Oregon State University were granted funds for two Doppler sodars to help characterize the spatial coherence of air flow above surface layer flows in light wind conditions and their connectivity to meandering low speed surface layer winds. This additional equipment augments the ongoing research of turbulence and structure of light wind conditions in stably stratified drainage flows. One sodar will be in a fixed position while the other may be moved to suit experimental requirements.

Improved Measurement System for Atmospheric Studies – Dr. Yannick Meillier, University of Colorado

Dr. Yannick Meillier at the University of Colorado received a grant to improve and expand the University of Colorado's Tethered Lifting System (TLS) with sensors and high-wind blimps, providing for concurrently operating two or three systems. The TLS consists of an aerodynamic blimp with a suspended line of multiple sensors to make measurements at either fixed altitudes or by profiling from the ground up to several kilometers altitude. The several sensor suites consists of low frequency temperature, velocity, pressure and humidity sensors as well as low-noise high frequency hot-wire and cold-wire sensors for fine-scale measurements in the challenging low turbulence conditions of the night time boundary layer. Low-frequency information from the TLS will be transmitted down to a ground station for real-time input into measurement planning as well as hazard avoidance. High frequency data are recorded onboard each sensor package. The new blimps permit increased stability and operation in high wind conditions.

Acoustic Tomography of the Atmosphere at the Boulder – Dr. Vladimir Ostashev, University of Colorado

Dr. Vladimir Ostashev at the University of Colorado was awarded funds to upgrade capabilities of the acoustic tomography array by acquiring two additional towers, and more speakers and microphones. The increased number and quality of speakers and microphones of the tomography array will allow reciprocal paths of transmission and reception to reduce the reconstruction of temperature and wind velocity fields by a factor of two. Integration of new towers and transducers into the array will also require acquisition of additional A/D systems, power amplifiers for speakers, microphone preamplifiers, and other equipment.

Acoustic Tomographic Array – Dr. Vladimir Ostashev, New Mexico State University

Installation and operation of the world's first three-dimensional acoustic tomographic array to simultaneously measure temperature and wind in the lower 10 m of the atmosphere over an 80 m square has been achieved. Cooperative field experiments in both day and night conditions have been conducted.

C. Tribal Colleges and Universities (TCU)

Three infrastructure awards were made under the DoD Tribal College and University program during FY09. J. Janecek-Hartman received funding to purchase soil and water quality analysis instrumentation together with computer hardware and software to enhance teaching programs in environmental sciences at the United Tribes Technical College. D. Burns received funding for the instrumentation necessary to establish remote sensing/geographic information system laboratory, chemistry laboratory, life sciences laboratory, and a general analytical laboratory that will be included in a new science building under construction at the Northwestern Indian College. C. Baker-Big Black of

Ft. Berthold Community College received funding for environmental equipment, meteorological instrumentation, and computer information technology.

D. Small Business Innovation Research (SBIR)

Multipulse Agile Laser Source for Real-Time Spark Spectrochemical Hazard Analysis in the Field – JMAR Technologies

There is a current need for laser sources that are capable of producing two or more pulses in short succession for optimizing the detection of both soils and hazardous materials in the field by real-time spectrochemical techniques. Employing the very innovative concept of using modification of a diode pumped Nd:YAG laser system modified around a dual Pockels cell geometry, JMAR Technologies is engaged in a Phase II to produce a small, rugged, and affordable multi-pulse laser source that can be integrated into a lightweight man-portable or robotic-deployed optical spectrochemical sensor system.

Real-Time Chemometrics and Sensor-Fusion (RT-CSF) Technology – ChemImage Inc.

This Phase-II SBIR project is to developing a means of combining spectroscopic data information from LIBS and Raman to enhance the individual performance of these two sensor technologies for the difficult problem of remote detection of explosives. Specifically, the effort is addressing the problem of fusing LIBS and Raman sensor data using a combination of chemometric and advanced multivariate statistical analysis-based spectral signal processing techniques. A prototype system is being developed that operates in real-time that allows testing of algorithm performance in limited field testing. Embedded processors or other hardware acceleration will be used to offer near real-time operation.

Compact Deminer's Probe – Scientific Applications & Research Associates Inc.

This Phase II SBIR effort is developing a LIBS-based prodder that will be integrated into a standard deminer's probe for the detection and discrimination of landmines from other buried object such as rocks, roots, and anthropogenic clutter) in the subsurface. The probe will connect to a backpack-mounted laser, spectrometer, and argon source through an armored bundle of optical fibers and tubing, thus placing the most expensive and bulky equipment away from the blast area and reducing strain on the deminer. The cable will attach to the probe through a rugged quick-release coupling, allowing rapid and tool-less probe replacement in the event of mine detonation.

Airborne Doppler Lidar Analyses and Adaptive Targeting System – Dr. David Emmitt, Simpson Weather Associates

The changes of wind speed and direction with height in the few km above the ground can have significant effects on dispersion of hazardous substances, sound propagation, aircraft operations, prediction of turbulence, and close air support. Operational forecast

models have great difficulty in producing accurate analyses and forecast of these winds. There is no current capability to measure the wind profiles in simple or complex terrain.

To capitalize on recent studies have demonstrated the capability of aircraft mounted Doppler wind lidars to measure wind profiles at about 30 sec (~ 1 km) intervals along the flight track. The on-board Airborne Doppler Lidar Analysis and Adaptive Targeting System (ADLAATS) under SBIR development is being developed to control the lidar system, process data on-board and periodically (~ 5 min) provide data to Army analysts. The system also provides intercomparisons with highest resolution operational weather forecast models, coincident in space and time.

The ADLAATS software concepts and capabilities are not restricted to manned aircraft. They are essential for battlespace sampling from UAS flights equipped with ultra-light, highly capable Doppler wind lidars under development at ARL/CIS/BED.

Low Parasitic Loss Waste Preprocessor for Forward Waste to Energy Conversion – Mr. Michael Cushman, Infoscitex Corporation

The conversion of materials in forward deployed military locations to reduce the need for logistics fuels and reduce the cost and logistics burden of disposing of encampment waste requires the development of innovative processing. The challenges is not only to design a robust unit process that can prepare materials for energy recovery at relatively small scale, but to design such a system that itself uses the minimal amount of energy possible to prepare the material. Here combat field waste is being converted to electricity via a waste-to-energy system with the goal to make the field service kitchens for Force Provider energy self-sufficient. The payoff is a reduction of JP-8 fuel usage by 95 percent, trash backhauled by 90 percent in field feeding operations, and the potential to make field service kitchens energy self-sufficient.

The Environmental Sciences Division is examining this topic through the work of Infoscitex Corporation on the Low Parasitic Loss Solid Waste Preprocessor for Forward Waste to Energy Conversion. The SBIR Phase II integrated a prototype onsite field waste to energy converter (OFWEC) to convert military packaging waste to electricity. The waste processing, drying, feeding, and gas production subsystems is to be packaged within a single modified 8' by 8' by 20' ISO container, having a gross weight of less than 10,000 lbs not including an external engine/genset. The system was capable of converting from transport to operational to transport modes with a minimum of time and effort after arriving at the field site, without using a forklift and operating continuously 24 hours per day to convert the relatively dry fraction of the of field feeding wastes to electrical power. It was estimated that the available waste stream contains 1250 lbs/day of relatively dry material. The producer gases fed to the diesel engine of a Tactical Quiet Generator (TQG) to generated electrical power from the producer gases. This work has garnered significant private venture capital and is likely to receive ESTCP funding.

E. Small Business Technology Transfer Program (STTR)

Time and Space Resolved Standoff Hyperspectral Imaging Explosives LIDAR Detector (TSR-SHIELD) – ChemImage Corporation in partnership with A3 Technologies Inc. and the University of Central Florida

This Phase II STTR program is developing a standoff optical sensor suitable for detection of explosives within complex environmental backgrounds. The objective is to combine LIBS and Raman spectroscopy, highly complementary spectroscopic techniques, and to employ state-of-the-art sensor data fusion algorithms to improve overall sensor performance in both natural and man-made environments.

F. Defense Program to Stimulate Competitive Research (DEPSCoR)

Five research grants were active under the Defense Program to Stimulate Competitive Research (DEPSCoR) program during FY09, which addressed environmental sciences research requirements. Following are brief summaries of these projects.

DInSAR Measurements of Soil Properties – M. Nolan, University of Alaska – Fairbanks

Work was completed on this 2006 DEPSCoR project is aimed at improving the signal-to-noise signal of differential interferometric synthetic aperture radar (DInSAR), when used to determine spatio-temporal variations in soil moisture. The study tested prior claims that InSAR phase could be used for this purpose. To demonstrate the phase and backscatter response of InSAR microwaves to changing real-world soil moistures, the ALEX (Atmosphere Land Exchange) model (was run to physically simulate how the vertical gradients in soil moisture change every 20 minutes over a five day period in response to two rainfall events (Figure 2a). The simulated soil used was based on a cornfield in Michigan before the corn had emerged and the model results were validated in the field by direct measurements as part of another study. The vertical soil moisture gradients from this model and used them in the 2-D FDTD simulator developed by the research effort to predict the phase (Figure 2c) and backscatter (Figure 2b) response of a SAR satellite. Comparing the responses (Figure 2d), it is clear that phase is at least as responsive to the soil moisture changes as is backscatter, if not more so. Phase seems to respond more sensitively to the initial dry-out than does backscatter. During the rain event, the relative change in phase is more than the relative change in amplitude during the brief dry-out during the rain events. Thus it seems clear that phase is not only sensitive to real-world soil moisture dynamics, but may even be a better proxy than amplitude.

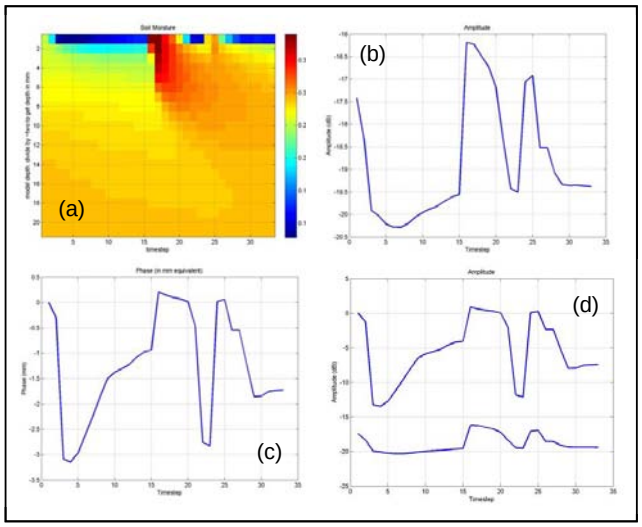


Figure 2. (a) Soil moisture from the Atmosphere Land Exchange (ALEX) model. A rain event began occurring about time step 15 (time steps are about 20 minutes each). Colors are VWC as fraction of 1. (b) Amplitude response predicted by the FDTD model to ALEX soil moisture. (c) Phase response predicted by the FDTD model to the Atmosphere Land Exchange (ALEX) model soil moisture. (d) Comparison of amplitude (bottom curve, dB) and phase (top curve, arbitrarily shifted and scaled). Note that the phase response is more sensitive to the initial dry-out (regardless of scale difference) and to changes during and in between rainfalls.

Results from numerical modeling, laboratory and field experiments, and satellite analysis, each validate that InSAR phase is sensitive to soil moisture with a strength and quality exploitable for useful measurements. However, it was observed that current SAR theory is inadequate to fully explain the research results. This research concluded that microwave phase is likely suitable as amplitude as a proxy for soil moisture, and that the design of any differential interferometric synthetic aperture radar operational system for soil moisture measurement on the spatial scale of meters, a penetration depth of centimeters, and moisture resolution of a few percent by volume should consider exploiting the phase component of the signal.

Identification of Hydrologic Similarity in Military Operational Environments – F. Ogden, University of Wyoming

This 2007 DEPSCoR project is working to understand hydrologic scaling similarity in different environments and then develop appropriate hydrologic modeling capabilities. Work with post-doctoral associate, N. Pradhan on the application of scaling laws two describe the scale-invariant topographical features that affect runoff generation has demonstrated that the application of topographical scaling relations greatly simplifies model parameterization, leading to what is effectively a one-parameter hydrologic model suitable for use in ungaged basins, a long-standing problem in hydrology with significant Army relevance. Data collection activities have continues at the ARO-funded Cerro Pelado study site in the seasonal tropics of Panama, as well as in the 414 sq. km Upper Rio Chagres watershed. These data are being used to test hypotheses regarding runoff generation, large woody debris transport, and rates of chemical weathering

Fusion of Remotely Sensed Data Sources for Modeling Eolian Soil Transport in Heterogeneous Terrain – N. Glenn, University of Idaho

This 2007 DEPSCoR project is undertaking the remote sensing and field research to acquire the knowledge necessary to develop new methodologies for modeling erosion and transport of soil by win in semi-arid environments. Remote sensing techniques for high-resolution topographic mapping, coupled with existing simulation models have been developed to predict where and under what conditions soil erosion or deposition will occur in semi-arid rangeland when subject to wind stress. New airborne data-fusion techniques are being developed for acquiring the high-resolution topographic data required to parameterize and validate the simulation model for geospatial scales of military relevance.

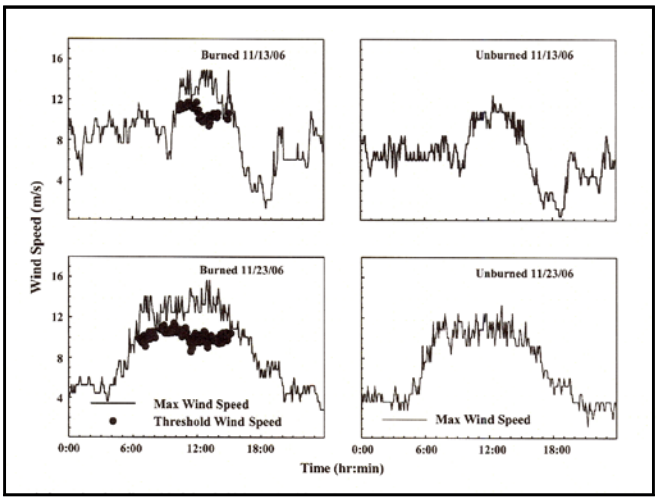


Figure 3. Examples of maximum wind speed and aeolian critical threshold determined for unburned and burned shrub steppe sites in southern Idaho on November 11th and 23rd, 2006. Maximum wind speed and threshold wind speed data are determined for 5-min periods.

Wind erosion of soil is an appreciable but unstudied event following fires in cold desert. Aeolian transport of sediment was examined for 12 months following fire in semi-arid shrub steppe on loess soils in southern Idaho (Figure 3). Sediment collectors were used to determine horizontal mass transport of soil and saltation sensors and anemometers were used to determine saltation activity (fraction of time having saltation) and threshold wind speed in an area burned in August and an unburned control site. Horizontal mass transport (per 30-day period) was negligible in the unburned area, but in the burned area was 5.40 kg/m in October and decreased to 2.80 kg/m in November and 0.32 kg/m in December. Saltation activity was high enough to determine threshold wind speeds only in the burn site during fall, when values ranged from 10.0 to 10.6 m/s. Sediment flux and saltation activity in the burned site became much less pronounced following the emergence of herbaceous vegetation in the spring. Post-fire sediment flux in the shrub steppe we examined was of greater magnitude but shorter duration than post-fire fluxes in warm deserts or sandier regions that experience more frequent wind erosion.

Context-Dependent Fusuion of Multi-Algorithm Systems for Detecting Explosive Objects – Professor Hichem Frigui, University of Louisville

This FY08 DEPSCoR project is undertaking research that will lead to autonomous algorithms for detecting buried explosive objects. Initially, current algorithms to detect larger explosive objects that are not necessarily landmines using vehicle-mounted GPR will be enhanced. Then a few specific algorithms will be identified and adapted for detecting landmines using multiple sensor systems, with a focus on GPR and EMI sensors. Different techniques for combining the RCA and SCAD algorithms to produce a single robust and fast clustering algorithm and various decision-level fusion methods for the second step of the multi-algorithm fusion process will be investigated. Finally, how to best incorporate algorithm selection capabilities directly into the multi-algorithm fusion objective function will be studied.

Measuring and Modeling Hydrologic Fluxes and States from Aquifer to Atmosphere at Multiple Scales – Dr. Warren Barrash – Boise State University

The Atmospheric and Terrestrial Sciences programs jointly committed to a fundamental study into multi-hydrometeorology, with soil moisture as a cornerstone which integrates both disciplines. The principal scientific/technical goal of this research is to advance modeling/predicting of soil moisture and terrain hydrologic and engineering conditions for military mobility, operations, and planning at needed spatial scales (<1 to 10s to 100s to 1000s m) and range of time scales and climatic/ecohydrologic events for high-priority temperate semi-arid riparian and hillslope environments (i.e., similar to Afghanistan). The research seeks to develop novel methods for fusing data from a broad suite of instruments collecting data across a range of spatial and temporal scales and variable seasonality. The approach will use physically-based ecohydrologic models (principally tRIBS-VEGGIE) and data assimilation to link these data across scales up to sub-watershed scale in a way that conforms to the processes governing the redistribution of moisture and energy, as parameterized by the model. In particular we will use (and enhance) existing well-characterized research sites in riparian (Boise Hydrogeophysical Research Site, BHRS) and hillslope (Dry Creek Experimental Watershed, DCEW) settings in the semi-arid range-front environment near Boise, Idaho. Data generated from high-resolution models and from intermediate-scale lab tanks will be used for calibration, conditioning, and validation of the sub-watershed scale modeling. This project will also advance applications of and improvements on non-intrusive remote sensing and geophysical methods (such as ground-penetrating radar and electrical resistivity) to determine moisture content distributions, including extensions of point measurements and high-resolution field-scale control for calibrating and validating satellite remote sensing measurements and analysis. Results will contribute to DoD research priorities of advancing in-depth understanding of moisture and energy distributions and behavior for the important semi-arid environment type on micro (<m) and intermediate (lab tank) to macro (field and sub-watershed) scales. Specifically, the proposed work will enhance capabilities to predict properties, behavior, and environmental effects under a range of typical conditions at required spatial resolutions that support buried-object detection and military operations (e.g., mobility, engineering) through fusion of data from a spectrum

of scales. Also, this research supports the core missions of (a) environmental sustainability at bases and training sites and (b) environmental stewardship by providing process understanding and modeling tools to assist subsurface remediation at contaminated sites within the DoD complex (and elsewhere).

Meaningful advancement on the high-priority problem of accurate modeling of moisture states and fluxes at sub-watershed and field scales requires the availability and coordinated combination of hydrologic and geophysical expertise, well-characterized reference sites and complementary lab facilities at a variety of scales, and appropriate modeling platforms and measurement instrumentation. This proposal represents a synergistic opportunity to address this critical problem with a strong team at Boise State University (BSU) and significant collaboration with distinguished extramural collaborators and facilities where DoD-supported and also DOE research are being conducted.

IV. SCIENTIFIC ACCOMPLISHMENTS

Self-Supervised Mobility-Based Terrain Classification for Unmanned Ground Vehicles (UGVs) – K. Iagnemma, Massachusetts Institute of Technology

Unmanned ground vehicles (UGVs) in natural terrain are significantly affected by the mechanical characteristics of terrain they encounter. One approach for identifying mobility relevant terrain characteristics for terrain in direct contact with a vehicle's wheels, based on torque and sinkage measured under conditions of induced wheel slip. This approach has been validated using experimental data from a laboratory test bed and from a four-wheeled robot in an outdoor beach environment. To predict the mechanical properties of terrain several meters from the robot, a self-supervised learning framework was developed and is presently being tested using a mechanical terrain characterization algorithm developed during the first part of the study, along with a visual terrain classification system based on a support vector machine classifier. Experimental results from field tests with a four-wheeled mobile robot have demonstrated the viability of this approach.

The UGV "*TORTOISE*", shown in Figure 4a, is robot with four rigid aluminum wheels, specifically designed for terrain sensing experiments. For the terrain characterization algorithm, *TORTOISE* sensed wheel torque using a torque sensor mounted to the motor driving the right front wheel. A camera mounted on the belly of the robot captured images of the right-front wheel during experiments, for use in measuring absolute wheel sinkage, and a potentiometer measured the angle between the robot body and the right wheel pair. An approach for evaluating terrain traversability has been developed using *TORTOISE* that uses an optimization framework to find upper and lower bounds on the normalized drawbar pull subject to observed wheel sinkage and torque. The traversability metric used for terrain characterization is the non-dimensionalized drawbar pull (DP/W), which is a measure of the net available traction force between the wheel and the terrain, and the net traction force can be modeled via lumped forces acting on a

single, rigid wheel. If the drawbar pull is positive, the wheel can exert a force to move the vehicle in the desired direction of travel. Conversely, if the drawbar pull is negative, resistance on the wheel will slow the vehicle, possibly causing the UGV to become immobilized. The relationship between drawbar pull and the wheel slip ratio is illustrated in Figure 4b. By specifying the wheel slip to be a moderate value – neither very low where some easily traversable terrains exhibit small drawbar pull, nor very high where material transport around the wheel can affect drawbar pull – this approach ensures that the traversability metric provides a conservative estimate of the force that a wheel could apply to stop itself from sliding down a slope, or to drive up a slope.

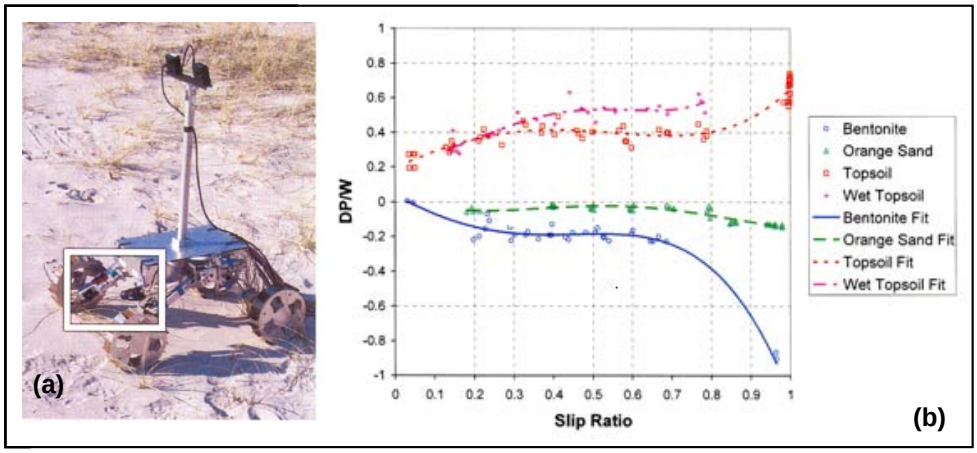


Figure 4. (a) The UGV TORTOISE showing the location of the local sensor suite and (b) non-dimensionalized drawbar pull (DP/W) as a function of slip for four terrain materials: bentonite clay, sand, topsoil, and wet topsoil (experimental data points and best fit curve).

Using data from a wheel-terrain interaction testbed with five different terrains and six different vertical loads, three methods were compared. The tightest bounds were achieved using a Bekker model with absolute sinkage, which demonstrated good consistency with experimentally observed drawbar-pull. This drawbar pull bounding method was also applied to data from a four-wheeled robot in a natural environment, and the associated drawbar pull predictions appear to be consistent with known physical characteristics of the terrains being traversed.

Wireless Sensor Network Based Subsurface Contaminant Plume Monitoring – T. Illangasekare, Colorado School of Mines

The primary goal of this project is to develop a novel, efficient, integrated, subsurface monitoring system, capable of capturing transient chemical plumes in real-time to assess the source and predict future plume behavior. This proof-of-concept research is aimed at demonstrating the use of an intelligent, self-organizing Wireless Sensor Network (WSN) to monitor contaminant plume movement in naturally heterogeneous subsurface formations to advance the sensor networking based monitoring for decision making and design. Also of specific interest, is how to adapt computational transport models to

utilize data from the WSN and how well this improves model predictions and to be used in intelligent remediation. Based on findings of proof-of-concept experiments in a 2-D test aquifer, a 3-D test aquifer was developed. The data generated in this synthetic aquifer instrumented with sensors and motes was used to validate developed software, inversion methods and modeling tools. A study, which focuses on the periodic inclusion of concentration data into a computational advection-dispersion transport model was performed using a synthetic data set. The next is step to use the replace this synthetic data with real data generated in the test aquifer.

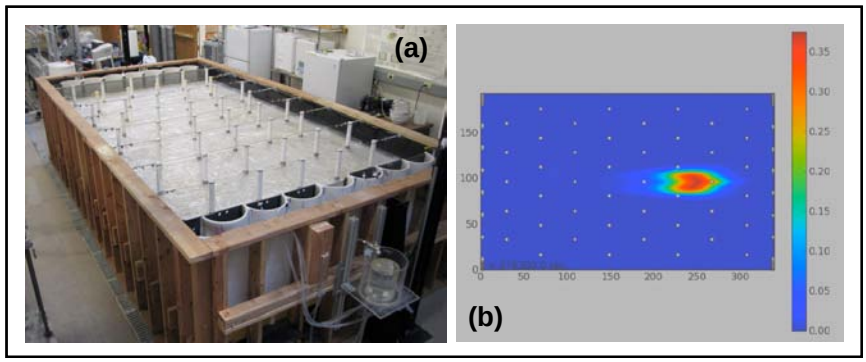


Figure 5. (a) The intermediate-scale synthetic aquifer facility at the Colorado School of Mines, overall tank dimensions are 8x16 feet with a maximum fill depth of 22.5 inches and (b) Animation of MT3DMS model of a centerline tracer plume. This snapshot is 76.5 hours after tracer introduction into reservoir S4. The white circles are well locations. The color scale is normalized concentration (C/C0).

Advanced Signal Processing for Disturbed Earth Detection – Signal Innovations, Inc.

Research has been undertaken that was directed toward improving the Army's ability to detect improvised explosive devices (IEDs) from imagery acquired by airborne surveillance systems. The specific objective of this effort is to develop advanced signal processing algorithms and software for SAR and EO/IR imagery to assess IED detection performance capabilities, and limitations. Detection of disturbed earth is a topic of high current interest and has been demonstrated using hyperspectral imaging to be effective in the Restrahlen band (approx. 8.2um to 10.7um). Multi-bandsystems operating in the Restrahlen band are desirable from a size, weight and power perspective compared to full hyperspectral systems. Hyperspectral data from the Airborne Hyperspectral Imager (AHI) are used to simulate a multi-band system operating in the Restrahlen band. A comparison of disturbed earth detection performance was made between the simulated multi-band and the full hyperspectral systems. A disturbed earth classifier was developed (Figure 6) that uses an unsupervised clustering algorithm based on a Variational Bayesian solution to a Gaussian Mixture Model (VBGMM). The VBGMM approach has the benefit of solving for full distributions of the GMM parameters and therefore can estimate the appropriate number of clusters to use via a compromise between data fit error and model complexity. The clustering operation is applied to a sample image to detect pixels with spectral similarities. Clusters representing disturbed earth are identified and the remaining clusters represent clutter. The high dimensionality of the

hyperspectral data requires an unrealistic number of samples for sufficient sampling. Dimensional reduction techniques (both linear and non-linear) were explored to reduce the hyperspectral data to a small number of dimensions to allow sufficient sample representation before using VBGMM clustering. Following the VBGMM based detection of pixels, a Relevance Vector Machine (RVM) approach was used to classify pixel objects based on size and shape features. For this approach and the data set provided, the multiband performance is comparable to that of the hyperspectral in detecting disturbed earth. The hyperspectral detector is able to discern subtler differences in disturbed earth, and by reducing hyperspectral dimensionality using non-linear spectral clustering using graph cuts, hyperspectral performance is improved.

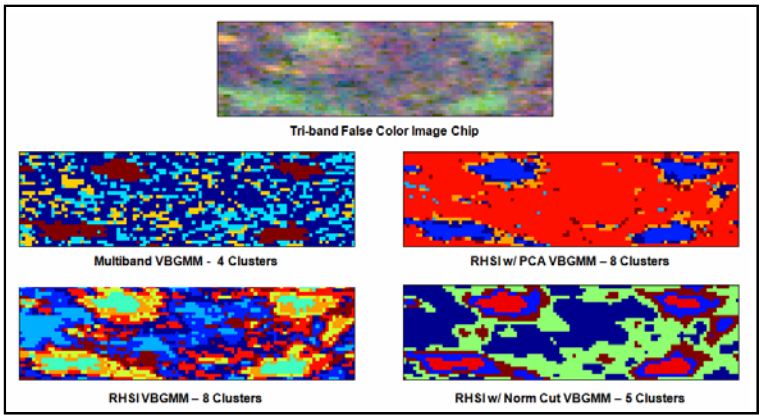


Figure 6. Result of the VBGMM clustering mapped back to regions in the training hyperspectral image chip. The training chip has four areas of recently disturbed earth in the greener areas of the tri-band false colored image chip. By comparing the clustered result for each chip, it is apparent how the different approaches are dividing up the disturbed earth regions. In the RHSI 47 dimensional space, there were 8 clusters found by the VBGMM. Because of the high-dimensional space, there are many gradations of disturbed earth separated into clusters, reinforcing the idea that the high-dimensionality allows for a less constrained clustering result. The multi-band result appears just the opposite. The clustering seems coarse and less intuitive with only four clusters found, but the disturbed earth areas are present and consistent. More clusters found using the RHSI PCA approach, but some have very low membership and seem to suggest that the objective function used in PCA is not necessarily optimal for segregating disturbed earth. The RHSI norm seems to be the most intuitive compromise between the full RHSI and the multi-band with 5 clusters found. The regions seem to clearly highlight a more annular clustering of disturbed earth moving away from the center of the areas.

Using the Maximum Entropy Principle as a Unifying Theory for Characterization and Sampling of Multi-scaling Processes in Hydrometeorology – R.L. Bras, University of California - Irvine

This research is exploring explore the *Theory of Maximum Entropy* as a unifying principle to characterize multi-scaling hydrometeorological parameters such as rainfall and soil moisture, and develop a *Maximum Entropy*-based design of data collection networks for the sampling of multi-scaling processes. The research is facilitated by first-principle based data collection network design using quantitative measure of information gain from the collected data, effective characterization of complex processes using

minimum observables, especially from remote sensing parameters, and an innovative model of land surface energy balance that potential enhances forecast of army operation related hydrological processes and micro-meteorological conditions using remote sensing information. Recent accomplishments include derivation and validation of maximum entropy solution of power-law distribution of river networks as the foundation of the proposed data collection network design, theoretical justification of non-informative priors in the mathematical expression of information entropy that plays a crucial role in all information entropy based formalisms, and development and preliminary test of a new model of surface heat fluxes based on the principle of maximum entropy production (as a derivative of the theory of maximum entropy), a major advancement in land surface hydrology.

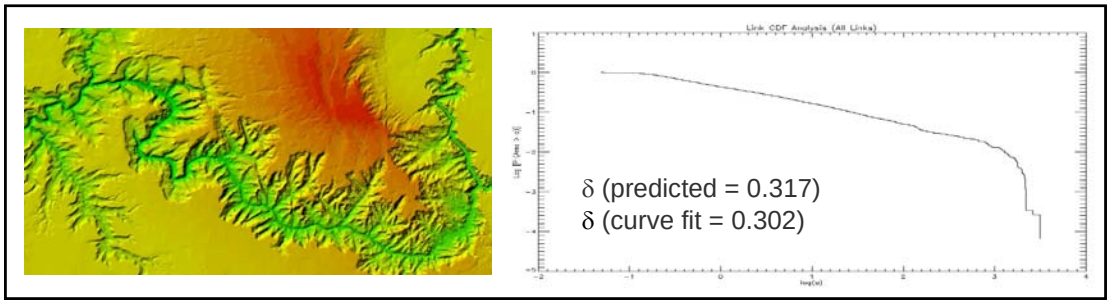


Figure 7. (a) Digital elevation map (DEM) of Grand Canyon from USGS data archives. The DEM data are used to compute the contributing areas, a, whose cumulative probability (CDF, a power-law function) in (b) which shows the power-law exponent (the slope of the straight line) predicted by the maximum entropy theory versus the empirical value obtained from the curve-fit of the DEM data.

Analysis of Doppler Lidar Data during Pentagon Shield – Dr. Rob K Newsom, Pacific Northwest National Laboratory, Richland, WA

The Pentagon Shield field experiment was conducted in May 2004. Two matched Doppler wind lidars were deployed to measure wind fields above the experimental domain. The lidars were located atop the Navy Annex building (Annex lidar), immediately to the west of Pentagon and at Bolling Air Force Base (Bolling lidar, operated by Army Research Laboratory scientists) approximately 5 km to the southeast of the Annex lidar, on the banks of the Potomac River. During the two week deployment both lidars performed overlapping volume scans and were operated more or less continuously. As indicated in Figure 8, the region of overlap between the two volume scans includes the Potomac River, East Potomac Park, the National Mall, and tidal basin areas.

Substantial initial effort was focused on acquiring data, assessing the quality of the observations, and developing appropriate techniques for data quality assurance and quality control. The first effort to combine observations from the two Doppler lidars was achieved during the latter half of 2008 and early 2009. Radial velocity data from the lidars were combined in a dual-Doppler analysis to retrieve low altitude horizontal vector wind fields using the technique described by Newsom, et al. (2008). Sample fields, taken

five minutes apart, are shown in Figure 8. Visual inspection shows significant speed and directional variability in space and time. Quantification of those variabilities is in progress.

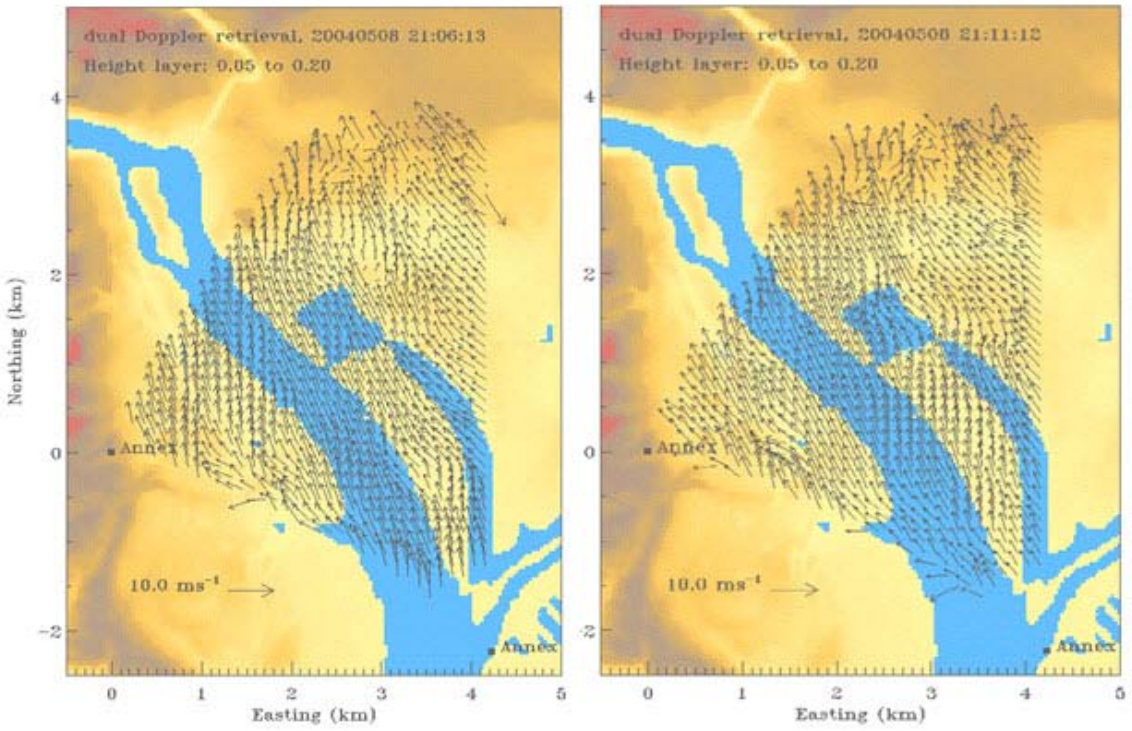


Figure 8. Dual Doppler wind velocity retrievals at 50-200m AGL during late afternoon of 5 May 2004 over Tidal Basin area of Washington, DC.

Dr. Newsom developed an entirely new technique to examine boundary layer structure using the signal to noise ratio (SNR), a relative indicator of aerosol concentration. Testing the hypothesis that aerosol layering – changes in aerosol gradients – should be found at gradients in the SNR, he plotted the potential temperature profile taken from rawinsonde ascents at successive times through the boundary layer with SNR and with the vertical derivative of SNR. Sample results are shown in upper and lower panels respectively of Figure 9 for the afternoon and evening beginning 8 May 2004. Many changes, some large, some subtle, in the temperature profile are clearly associated with SNR gradients. The decay of the afternoon mixing layer (no potential temperature gradient, constant SNR) into multiple layers of a strongly stable, multi-layered boundary layer with varied aerosol content is clearly evident.

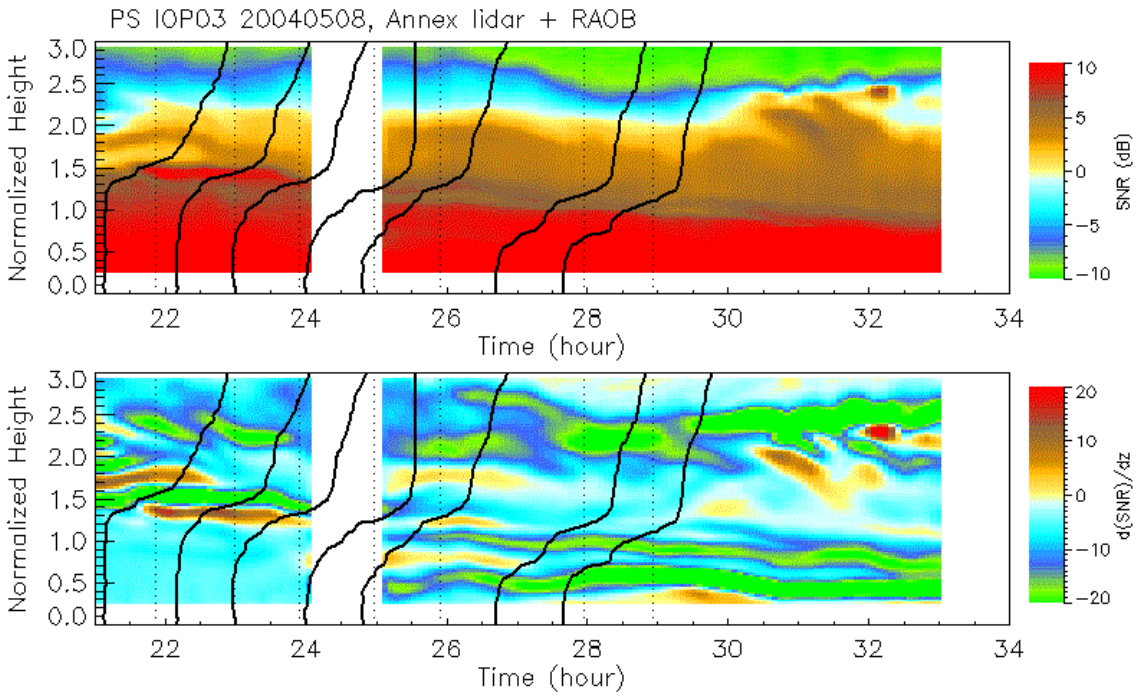


Figure 9. Vertical profiles of signal-to-noise ratio over time (upper) and d(SNR)/dz (lower) measured at Annex lidar (background) and potential temperature from radiosondes released nearby (dotted lines) for beginning on 8 May. (Sunset is ~ 2400 UTC)

More recently the PI has extended this analysis to retrieve horizontal components of the wind field as a function of horizontal position and height. This new analysis was conducted using the grid shown in Figure 10. Each of the numbered grid points correspond to the locations of so-called virtual towers, i.e. locations where vertical wind profiles are computed from the dual- Doppler data. For this analysis, profiles were computed using a 15-minute averaging period. For a given 15-minute period, a subset of measurements that lie within a 500-m radius of a given virtual tower were selected. These observations were then further segmented according to height. A least squares method was then applied to this subset of data to compute the U and V components of the wind field. This process was repeated for all height layers, virtual towers, and averaging periods. Analysis codes were developed using the procedure outlined above, and then applied to the entire lidar data sets.

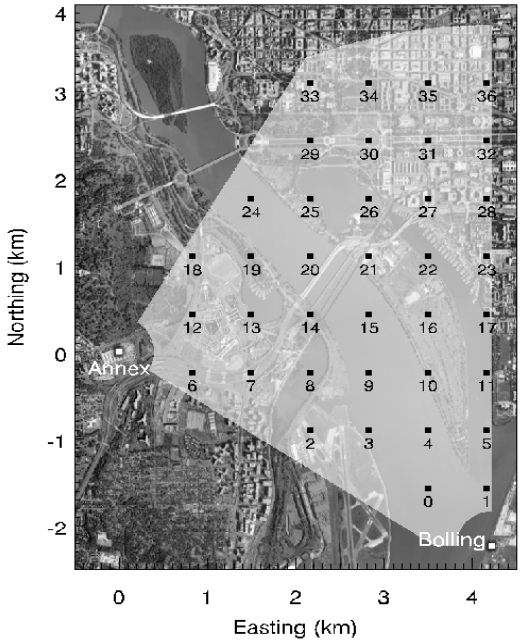


Figure 10. Aerial image of the study area showing the locations of the Bolling and Annex lidars. The area in light contrast illustrates the dual-Doppler coverage area. The locations of virtual towers are labeled 0 through 36.

The dual-Doppler coverage area is bisected by the Potomac River and East Potomac Park, with dense urban development on either side, resulting in a step change in the aerodynamic surface roughness. Indeed, a preliminary inspection of the results shows pronounced effects on the wind profiles due to heterogeneities in surface characteristics under certain stability conditions.

Figure 11 shows a series of wind profiles along an east-west transect over the Potomac River during an early evening period (~2340 UTC or 1940 EDT) on 4 May 2004. Sunset at this time of year occurs at approximately 00 UTC (2000 EDT). The mean winds in this case are from the southwest, and a low-level jet structure is clearly evident. Wind speed profiles at towers 12 and 13 show strong positive shear below the 200-300m level. These towers are located over the urban area (on the Virginia side of the river). By contrast, virtual towers located over and downwind of the river (15, 16 and 17) show a dramatic increase in wind speed in the lowest 200-300 m compared to the upwind sites. This is presumably the result of the abrupt change in surface roughness as the flow moves over the river. This case tends to be characteristic of afternoon and evening periods. Studies of more stable conditions are in progress.

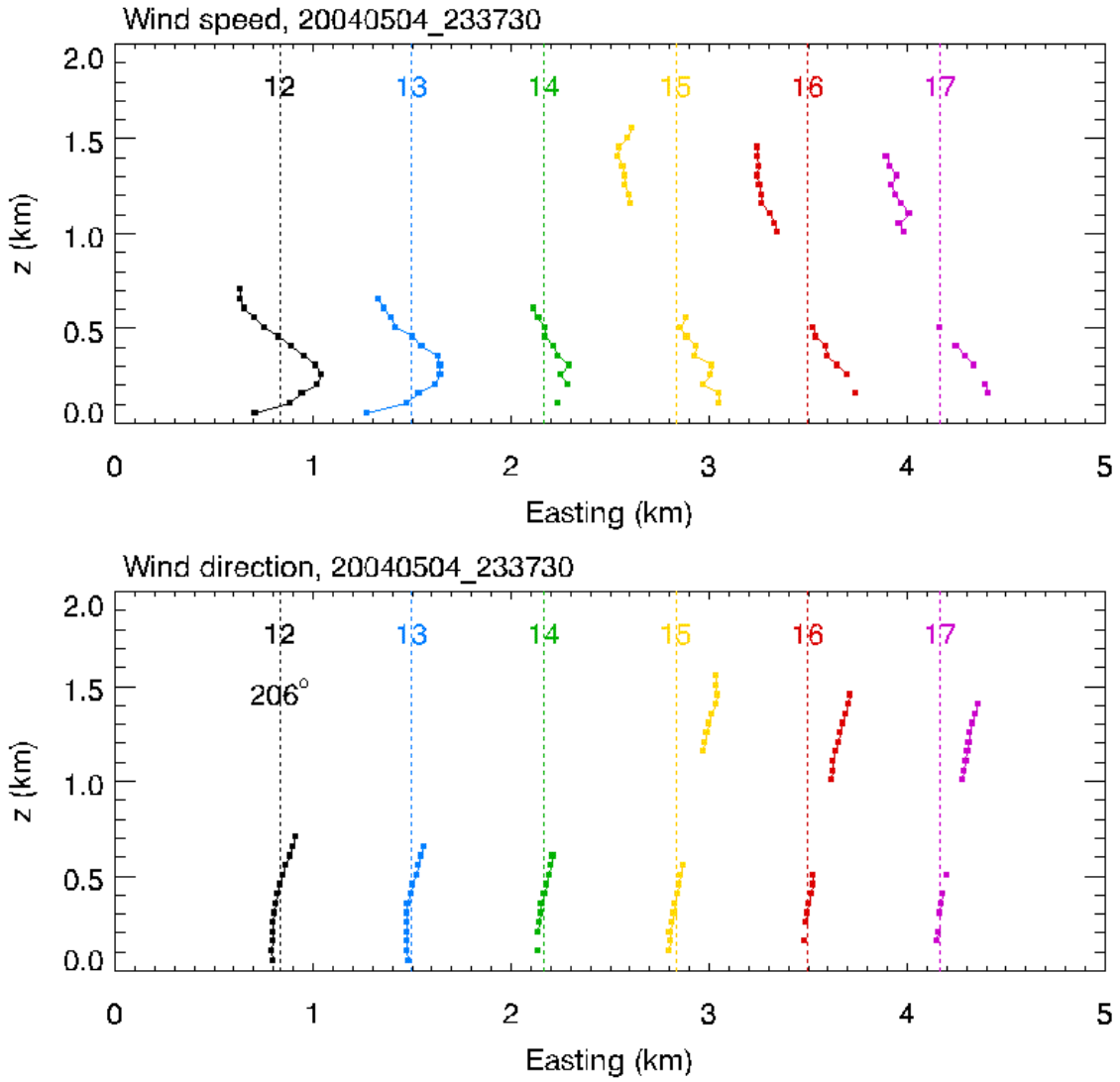


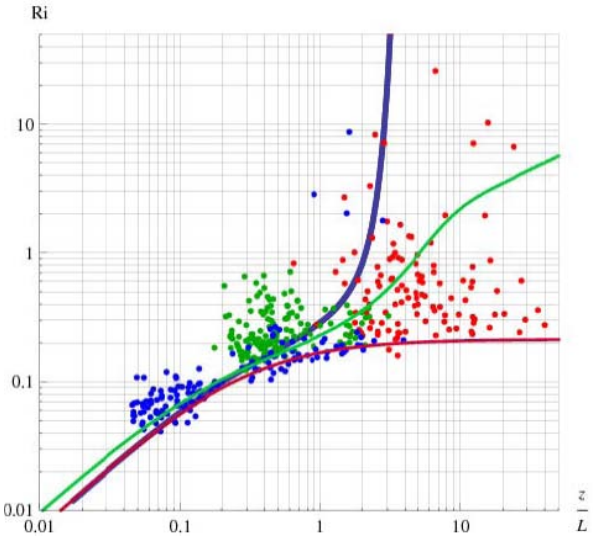
Figure 11. Profiles of wind speed (top) and wind direction (bottom) along an east to west transect for 4 May 2004 at 2337 UTC (1937 EDT). The numbers shown near the top each panel indicate the location of these profiles in Figure 10. The vertical dotted lines indicate the x (easting) coordinate of each profile (relative to the Annex lidar), and provide a fixed reference of wind speed (top) and wind direction (bottom). The reference wind direction is shown below the "12" in the bottom panel.

Further implementation and refinement of the QNSE model of turbulence – Dr. Boris Galperin, University of South Florida

An international team of scientists led by Dr. Boris Galperin at the University of South Florida has been developing the Quasi-Normal Scale Elimination (QNSE) model applicable to numerical modeling of stably-stratified waves and turbulence. This model, applicable to stratified geophysical turbulence in the atmosphere and ocean and giant planets, was developed to address the very difficult problem of modeling temperature, moisture, winds, waves and turbulence in the lower atmosphere at night. Research showed that the model worked very well within the fluid, but was not consistent with

techniques used in numerical models to connect the surface conditions (bottom boundary) with the fluid away from the boundary – i.e. the first grid point in the fluid. Furthermore, most boundary layer parameterizations tend to show a warm bias in stable conditions. Research suggested the inconsistencies were related to biases in temperatures and fluxes produced by the models.

The Monin-Obukhov similarity hypothesis is the common approach to connecting the surface properties with the fluid in models. While valid for neutral flows, experimental evidence is used to adjust for stability. The similarity parameter z/L can be expressed as a function of the Richardson number, eddy viscosity, and eddy diffusivity and QNSE relates the Richardson number to eddy diffusivity and viscosity. Combining the results leads to an unique representation of the similarity parameter using QNSE results shown in Figure 12 . With QNSE and the lack of critical Richardson number, the z/L has an asymptotic value of ~ 3 in keeping with Marht's analyses for very stable conditions.



Blue – QNSE 2008
Green – Holtslag & Beljaars 1991
Red – Businger & Dyer 1974

Figure 12. Richardson number, Ri, as function of Monin-Obukhov parameter, z / L for QNSE and other representative parameterizations.

Results from an operational forecast model for the Arctic displayer in Figure 13 show the forecasts over a 5 day period could not predict very cold surface temperatures (below -20 C) observed (red line) at the Sodankylä, Finland site. When using the QNSE surface layer parameterization, the same model, using ONSE turbulence closure and surface layer parameterization, captured the very cold temperatures, suggesting that the QNSE helps eliminate the warm bias for cold Arctic conditions.

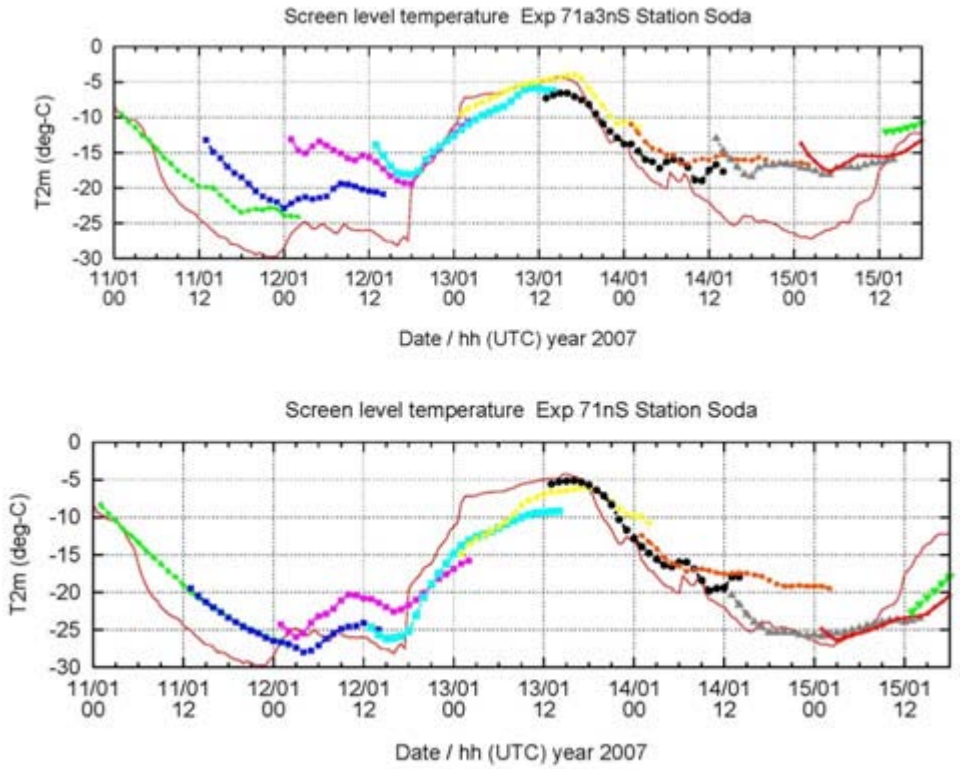


Figure 13. Successive 24-hour temperature forecasts for Sodankylä, Finland site without (upper) and with (lower) QNSE closures using the same operational forecast model. Solid red line is the observed temperature.

Research has been initiated to extend the QNSE approach to weakly unstable conditions characteristic of fog and low cloud conditions.

V. TECHNOLOGY TRANSFER

The ARO Terrestrial Sciences program was very active in technology transfer during the past year. Organized by the ARO Terrestrial Sciences Program and hosted by the COE-ERDC Topographic Engineering Center, the 12th Landmine and Explosive Object Detection Research Review Meeting was held on 28-29 January 2009. More than 60 people from DOD organizations (National Geospatial-Intelligence Agency, Space & Missile Defense Command, Joint IED Defeat Organization, ARL Sensors & Electronic Devices Directorate, ARL Army Research Office, Army CERDC-NVESD Countermine Directorate, Office of Naval Research, Naval Research Laboratory, Naval Surface Warfare Center, & US Naval Academy), academia, and industry. The meeting presentations described recent progress and developments for NGA-, SERPD-, Army-, and Navy-sponsored basic and applied research in the broad area of explosive device (landmines, UXO, & IEDs) detection and discrimination and provided an open forum for principal investigator-laboratory interaction.

Three workshops were sponsored by the ARO Terrestrial Sciences program during 2009. A workshop on "Integration of New Methods is Soils and Geomorphology Applied to Cultural Resources Management on Military Lands" was held in San Diego, CA on 21-22 October 2008, jointly sponsored by the ARL Army Research Office and the Navy Facilities and Engineering Command Southwest. A workshop on "Failure Detection in Earthen Embankments" was held at the COE-ERDC Waterways Experiment Station in February 2009, sponsored jointly with the Army Corps of Engineers, Department of Homeland Security, and Department of Agriculture. A "Tropical Hydrology" workshop, jointly sponsored by the Army Tropic Regions Test Center and Smithsonian Tropical Research Institute, was held in Panama City, Panama in March 2009.

Planning Systems Inc. is developing a forward-looking ground penetrating radar (GPR) explosive detection system equipped with infra-red cameras (FLIR) as well as a vehicle mounted downward-looking GPR landmine detection system. Professor J. Keller at the University of Missouri – Columbia is undertaking research in image processing, sensor fusion and signal processing techniques for the forward-looking ground penetrating radar (FLGPR) explosive hazard detection system equipped with infra-red (IR) cameras. The ultimate goal is to utilize multiple sensing modalities together with FLGPR to increase IED detection with low false alarm rates. Novel image modality registration algorithms and updated ATR algorithms were developed (Figure 14), which opens up the opportunity for true sensor fusion and transitioned to the Army CERDC Night Vision and Electronic Sensors Countermine Directorate.

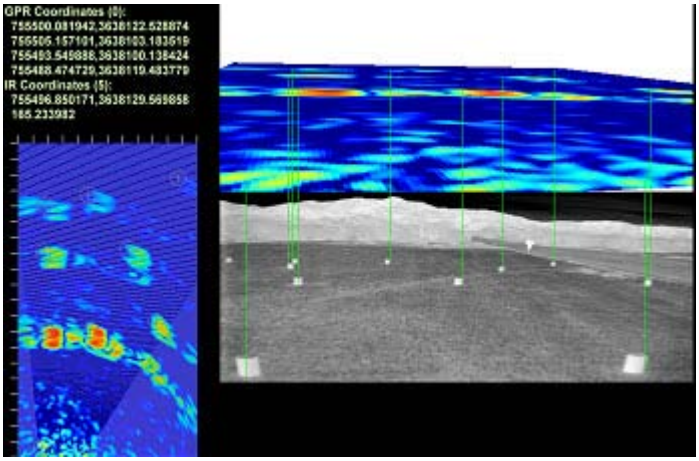


Figure 14. Example of FLGPR and IR co-registration. Left image is an FLGPR scan with target ground-truth locations shown by crosshair. Right image shows FLGPR scan projected into the camera reference frame. Green lines show FLGPR-IR correspondence.

Other instances of technology transition to CERDC Night Vision and Electronic Sensors Countermine Directorate included improved techniques for self-signature removal in GPR from Duke University to CERDC-NVESD Ground Standoff Minefield Detection System (GSTAMIDS) and Handheld Mine Detection Systems program and advanced signal processing and target classification algorithms for landmine and IED detection provided to the U.S. Army for the Husky Mounted Mine Detection System (HMDS) by the Universities of Florida, Louisville, and Missouri.

A method for soil moisture estimation from Colorado State University was transitioned to ARL-CISD Battlefield Environments Directorate for incorporation into Army Integrated Weather Effects decision aid, a new technique for proper orthogonal decomposition reduced order model was incorporated into COE-ERDC Coastal and Hydraulics Laboratory Advanced Distributed Hydrology simulator, experimental data and modeling results on the thermal properties of sands with different mean grain sizes under varying moisture and porosity conditions under drainage/wetting/drying cycles from the Colorado School of Mines was provided to the COE-ERDC Countermine Testbed Program for comparison with Army field data.

The QNSE model (above) was accepted for inclusion in the March 30, 2009 release of the Weather Research Forecast (WRF) model – currently used by the US Air Force providing weather support to the Army. Multiple national and international users have incorporated it into their research and evaluation capabilities showing improved modeling capabilities. The new parameterization for the Monin-Obukhov length as a function of Richardson Number has also been implemented giving substantial improvement in forecasts.

Dual Doppler analyses of wind flows above a sub-urban area of Oklahoma City by Dr Rob Newsom and Dr Ron Calhoun calculated the scale of the principal energy containing horizontal eddies as a function of stability. These results are being used in multi-agency assessments of important scales required to characterize urban test beds and the associated measurement systems.

Finally, ADLAATS software was used for analyses of boundary layer wind fields in incipient tropical storms by ONR.

VI. DIVISION STAFF

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I. PROGRAM OBJECTIVES

Basic research in the life sciences greatly increases the ability of the US Army to identify and modulate molecular and physiological reactions and processes that affect soldier cognitive and physical performance capabilities, to protect soldiers, and to conceptually identify and experimentally characterize and develop unique materials and processes for future exploitation in engineered systems. Basic research in life sciences also has the potential to improve Army logistics by reducing operating costs. This research seeks to generate the means by which biological processes and products will provide materiel for Army use, to increase economic and environmental affordability by reducing operating, maintenance, and synthetic processing costs and by-products, to optimize human cognitive and physical performance, and to prevent the deleterious effects of chemical, biological, and physical agents from interfering with Army operations.

Research program activity in the life sciences is structured to emphasize an appropriate balance between capture of breakthrough scientific opportunities from the life sciences research community and alignment with Army and U.S. Department of Defense (DoD) science and technology objectives, and support of Army current and future demonstrations and fielded items, where applicable. While aimed at enabling novel capabilities, program efforts focus on providing solid scientific underpinnings for biologically based technology contributions to fulfilling Army operational requirements. Within the framework of Army Transformation goals, emphasizing the Future Objective Force, it is expected that life sciences research will impact significantly the areas of force projection and protection, battle command, intelligence, maneuver, mobility, and logistics. For the warfighter particularly, basic research in the life sciences can form the basis to minimize injuries from hostile actions through novel protective fabrics, accelerate wound healing and promote tissue regeneration, produce lighter and easily rechargeable electronic equipment, promote a secure environment from biological hazards, and maintain soldier performance capabilities at optimal levels.

II. RESEARCH PROGRAM

A. General Information

Implementation of a strategy for meeting the above program objectives involves basic research support provided by a number of sub-disciplines including, but not limited to, biochemistry, biophysics, molecular biology, genetics, genomics, proteomics, bioinformatics, cell biology, microbiology, physiology, psychology, pharmacology, systems biology, and cognitive neurosciences. These areas encompass studies that range from the molecular, cellular, and organismic levels through biotechnology, sensory perception and psychological studies on human performance. The U.S. Army Research Office (ARO) life sciences program supports efforts at the Natick Soldier Systems Center (NSRDEC), the Edgewood Chemical Biological Center (ECBC) of the Army Soldier Biological Chemical Command (SBCCOM), the Army Research Institute (ARI), the Army Corps of Engineers (COE), the Army Medical Research and Materiel Command

(MRMC), and the Human Research and Engineering Directorate (HRED), Sensors and Electronic Devices Directorate (SEDD) and Weapons and Materials Research Directorate (WMRD) of the Army Research Laboratory (ARL). Each major research area supports identified needs within appropriate Army mission areas. There is joint funding of several projects with other agencies. The Life Sciences program also supports some multidisciplinary research projects jointly with other ARO divisions.

ARO-Life Sciences (ARO-LS) core program comprises research support in a number of subfield "thrust" areas, each representing an individual workpackage for ARO-LS Division funds, with additional support from other sources for projects falling within the purview of these subfields or representing entirely separate workpackages.

The past year has seen a continuing involvement of ARO-LS Division staff members with DARPA and DTRA research program planning activities and other activities related to management of portions of the DARPA and DTRA research project portfolio that parallel the life sciences interests of the Army Research and Development community. These not only take the form of typical DARPA and DTRA agent functions (*i.e.*, active program management), but also service as panel members for evaluative review processes for DARPA and DTRA consideration of informal and formal proposal submission in various programs. Active areas of collaboration now include regeneration, surviving blood loss, brain-machine interfaces, prosthetics, peak soldier performance, signatures of laboratory-grown bio-agents, physical intelligence, and resistance to stress.

B. Thrusts and Trends/Workpackages

The activities of the ARO-LS Division can be grouped into four program areas or workpackages that describe the "theme" or "thrust" areas as identified within the existing ARO Broad Agency Announcement. Each of these four program areas address the strong potential for emerging fundamental knowledge in biotechnology to make rapid and highly innovative contributions in the areas of materials, sensors, systems and processes, including striking advances for human (*i.e.* the Soldier), as well as engineered systems application.

1. Neurosciences - This workpackage covers non-medically oriented research designed to elucidate the fundamental physiology underlying perception, cognition, neuro-motor output and possible non-invasive methods of monitoring cognitive states and processes during normal activity. The research areas include perceptual and/or psycho-physiological implications of mind-machine interfaces ranging from optimizing auditory, visual and/or somatosensory display and control systems based on physiological or psychological states through modeling of individual cognitive dynamics and decision making. The research programs in this workpackage have expanded into areas involving more direct sensing of brain states as well as into projects examining how other species in the animal kingdom can serve as models for engineered systems. The brain sensing projects include research into alternative non-invasive input and outputs techniques including tactile communications systems and ultrasonic brain circuit modulation. Ongoing projects are working with neural biofeedback to sharpen and differentiate brains

states for possible direct brain-machine communication and to determine how closely humans can approach hemispheric sleep as seen in some migrating birds and in dolphins. Finally, both cell culture and social insect models are being used to develop better understanding of living neural networks and swarm intelligence for eventual application in Army systems.

2. Microbiology - This workpackage focuses on fundamental studies in microbial physiology, genetics, ecology and evolution. Microbes are distributed throughout nature and are, in fact, essential for eukaryotic viability. However microbes can also cause problems ranging from catalyzing materiel degradation to life-threatening infections. Therefore, understanding how these organisms thrive and adapt to various environmental niches is of great importance. Included in this workpackage are studies to understand antimicrobial resistance mechanisms; microbial community interactions including biofilm formation, cell-to-cell communications, population dynamics & host-pathogen/symbiont interactions; studies of organisms that are not culturable; studies of organisms at the single cell or mixed population (*e.g.*, metagenomic) level; and studies of organisms that have adapted to grow or survive in extreme environments. Also included is research on biochemical and physiological mechanisms underlying the biodegradative processes in normal, extreme, and engineered environments; the properties of materials that make them susceptible or resistant to biological attack; studies of microbiological mechanisms with potential for contributing to the remediation of sites contaminated with toxic wastes; and the development and exploitation of microbial systems for unique biotechnological applications and bioengineering processes.

In keeping with interests of the Corps of Engineers, research projects with potential impact on environmental bioremediation continue to be pursued. These projects are aimed at understanding the fundamental microbiological processes and molecular mechanisms involved in recognition, uptake and enzymatic degradation of militarily relevant pollutants. Recent data indicate that in most cases environmental bioremediation results from the actions of multiple microbial species working synergistically rather than the actions of a single species. This observation emphasizes the importance of basic research to understand intercellular communication, chemotaxis (celllular movement based on environmental factors), quorum sensing (coordinated sensing and behavior by decentralized groups such as single-celled organisms), population dynamics, and biofilm regulation. Two efforts to develop a naphthalene dosimeter have also been funded with close coordination with the Corps.

3. Molecular Genetics - This workpackage emphasizes basic research in molecular genetics and genomics that will enable optimization of soldier cognitive and physical performance, soldier protection, and Army logistics. This includes human performance and protection under both normal conditions, and when affected by a variety of stressors that are likely to be encountered in battlefield situations, such as dehydration, heat, cold, sleep deprivation, fatigue, caloric insufficiency, microbial factors, and psychological stress. Genetic and genomic research areas include identification and characterization of gene function, gene regulation, genetic interactions, gene pathways, gene expression patterns, mitochondrial regulation and biogenesis, nuclear and mitochondrial DNA

replication, mutagenesis, oxidative stress, DNA repair, and regeneration. The research work plan also encompasses molecular responses to pathogens, pathogen identification, and pathogen inactivation, as well as host-pathogen interactions, and host components of infection and resistance to infection. This program also supports basic research into mechanisms of DNA stability and maintenance of DNA integrity in prokaryotic DNA as well as eukaryotic nuclear and mitochondrial DNA. This program also supports development of new biomaterials and bioproduction methods, and other advances in biotechnology methods and applications.

4. Biochemistry - This workpackage focuses on fundamental studies in biochemistry, structural biology, cell biology, and biophysics that will facilitate the development of novel systems and processes to enhance soldier protection and performance. Research areas include protein and nucleic acid structure-function relationships, enzymology, molecular recognition, signal transduction, cell-cell communication, macromolecular structure, and synthetic biology. This program also supports basic research in protein engineering for novel or enhanced enzymatic function, sensing capabilities of biomolecules and cells, biomimetic and bio-inspired systems, biomolecular power and energy generation, structural studies of molecular and macromolecular organization for novel materials or surfaces, and relevant systems biology studies involving the modeling and testing of complex biological networks at both the genetic and multiscalar levels. There is also significant interest in novel methods for biomolecule production, purification, and structure determination.

The Biochemistry research thrust has been given a substantial boost most recently via the successful launching of the Army University Affiliated Research Center, the Institute for Collaborative Biotechnologies (ICB). The vision for ICB is that it will serve as the network "hub" for conducting, assessing, coordinating and leveraging extramural cross-disciplinary biotechnology research on behalf of the Army. The ICB conducts unclassified scientific research in four areas of emphasis, as described further in Section III-B, *University Affiliated Research Center (UARC).*

C. Research Investment

1. Microbiology Program - The FY09 investment in the Microbiology workpackage totaled close to $4.0 million. Of this, core program funds amounted to approximately $1.4M in support of fourteen research projects. The remainder is from projects funded by PECASE, SBIR, STTR, MURI, and DURIP programs, and DoD customers. Among the performers within this workpackage are the University of Washington, Mount Sinai School of Medicine, New York University, the University of California - Irvine, Northeastern University, Harvard Medical School, and the University of Connecticut.

2. Molecular Genetics Program - The FY09 ARO Life Sciences core program investment in the Molecular Genetics workpackage was approximately $1.4M for eleven projects. Core program support was supplemented with funding from Office of the Secretary of Defense (OSD) and other DoD sources, including $22M from DARPA and DTRA, $2.4M from MRMC, $235K from non-lethal funds and OSD, $3.0M of MURI

funds, $693K from SOCOM, and $1.5M in SBIR and STTR funding. DARPA support is focused on soldier performance and protection, and is highly integrated with Army objectives. SBIR and STTR objectives are currently focused on identifying compounds that improve mitochondrial performance capabilities and developing a naphthalene dosimeter. This program supports 108 active research projects, which include investigators at leading universities such as Yale, Princeton, the University of Washington, and Stanford.

3. Neuroscience Program - The Neuroscience program received a funding boost of approximately 10% to $1.3 million in FY09 and currently supports seventeen single investigator projects. In addition, two further projects were supported with $21.3M in MIPR funds from MRMC and OSD and are being completed. The MURI on "Bio-integrating Structural and Neural Prosthetic Materials" is in its third year and funded at $1M per year. Based on the research progress demonstrated in this area, the MURI team successfully competed for two years of final option funding. Two HBCU/TCU projects were launched, one in infrastructure support and the second, partially supported with core funds as well, on the mechanics of the neuromuscular junction. A new SBIR project in tactile integration measurement as an indicator of mild traumatic brain injury also began, and was awarded $119K. Additionally, four new DURIPs proposals investing $525K were started. New external funding was also attracted to the program in FY09, including $565K from DARPA. In FY09, ARO also began managing $15.4M of JIEDDO funds to support projects in the physiology of traumatic brain injury and its amelioration. In addition, funds of $334K were introduced that will support single investigator projects in neural interfaces and basic neuroscience.

4. Biochemisty Program - The total FY09 investment in the Biochemistry program is $14.6 M. The ARO core funds invested in the Biochemistry program currently support nine investigators with a total of $1.08 M. The Institute for Collaborative Biotechnologies entered its fifth year with a total of $9.5M in 6.1 funds and $4.0M in 6.2 funds for FY09. Research groups supported by core funding are located at MIT, Princeton, Cornell, the University of Kansas, Arizona State University, the University of Florida, and the University of California at Santa Barbara.

D. Workshops and Symposia

Building Neural Interfaces for Neural Prostheses; Beyond Brain Machine Interface: Motor, Cognitive, and Virtual - Minneapolis, MN, 2 September, 2009**.** This ARO sponsored workshop covered recent development in brain computer and brain machine interfaces which have captured the attention and imagination of students, engineers and the scientific community. In this arena, building the neural interfaces and their ability to control prosthetic devices has posed one of the biggest challenges and opportunities to do pioneering work in the fields of interface technology, signal and information analysis methods and algorithms, and interfacing to prosthetic machinery. This workshop reviewed the current state of the art in neural interfacing technologies and presented cutting edge applications to controlling upper limb dexterous prostheses. The lectures reviewed technologies spanning microelectrodes, large scale integrated circuits,

packaging these systems for implantable and wearable applications, neural signals recording, analysis and decoding. Finally, through simulations and demonstrations, application of the neural interface technology to control dexterous prosthetic manipulators was illustrated.

III. SPECIAL PROGRAMS

A. Multidisciplinary University Research Initiatives (MURIs)

The MURI program is a multi-agency DoD program that supports research teams whose efforts intersect more than one traditional science and engineering discipline. These awards constitute a significant part of the research programs managed by the ARO-LS Division. The unique aims of the MURI program were described in detail in Chapter 3, *PROGRAM IMPLEMENTATION*.

1. Discovering Materials Suitable for Bio-integration - The MURI "*Bio-integrating Structural and Neural Prosthetic Materials*" began in 2006 and is led by Dr. Paul Cederna at the University of Michigan. The investigators are completing their third year investigating materials and methods for use in limb repair. This MURI successfully competed for an extension of two years of additional funding, based on the promising results uncovered by the research team.

The objective of this MURI is to create structural and interconnective bio-integrating materials for future limb repair, covering the entire interface between living and non-living structures. By putting prosthetic materials research on a firm theoretical foundation based in physiological interfaces and principles, the current art of anatomical and physiological compensation can be placed on a scientific rather than an empirical foundation. The Michigan scientists have further developed a method for directly connecting with peripheral nerves, using a soft, electrically conductive scaffolds that can be filled with muscle cells to act as targets for propagating axons to the point that this project has created a spin-off project currently being considered for funding in order to advance the state of knowledge to the point of clinical trials. The ability to design and build intelligent, adaptive, active devices using such engineered biological/non-biological interfaces could ultimately permit a complete return to duty for military personnel with no diminution of ability as well as producing a seamless body of knowledge allowing augmentation of limited function to normal or even enhanced levels of performance.

2. Investigating Brain Signals as Method for Decoding Unspoken Thoughts - The MURI "*Silent spatialized communication among dispersed forces*" was awarded in 2008 to a team led by Dr. Thomas D'Zmura at The University of California Irvine. This team is investigating whether electroencephalographic (EEG) readings of brain, which measure electrical activity along the scalp produced by the firing of brain neurons, can be used to determine if and how thought words can be decoded.

This MURI leverages the breakthroughs in neuroscience and cognitive science uncovered in recent years. These breakthroughs, when coupled with technological advances in

analytic hardware and software, have significantly advanced research progress on brain-computer interfaces (BCIs) that decode the activity in brain networks. The effort is nearly analogous to the development of speech recognition software; however, rather than having sound as the input, the inputs will be EEG signals.

This MURI is one of a pair of active awards intended to pursue complementary research goals—the other award is managed by the Computing Sciences Division and is titled "*A Brain-Based Communication and Orientation System*." The concerted research effort will attempt to develop a computational model that could i) decode intended mental speech, and ii) decode the direction of the attentional orientation of an individual based solely upon recorded activity from the surface of the scalp. Early progress to date has shown that considering the formants (frequency band components of speech that correlate to specific structures and muscles in the vocal tract) allows a much better prediction of the intended sounds than using either syllables or words themselves. Further, EEG indicators for exactly when an individual begins thinking a particular sound have also been seen, resulting in much better synchronization of the machine analyses with the user's intent. Evolution of this research thrust beyond this MURI could lead to direct mental control of engineered systems by thought alone ranging from automobiles through construction equipment to computers.

3. Identifying Cultural Factors Influencing Negotiation and Collaboration - Funding began in 2008 for the following two MURI teams to identify adequate theory for understanding and predicting how culture impacts negotiations.

- *Dynamic models of the effect of culture on collaboration and negotiation,* led by Dr. Michele Gelfand at the University of Maryland
- *Modeling Cultural Factors in Collaboration and Negotiation,* led by Dr. Katia Sycara at Carnegie Mellon University

These research teams are identifying any cultural differences that affect behavior in intercultural interactions under conditions of interdependence, such as orientation toward collaboration, conflict management styles, and communication norms. The investigators are using their observations of differences among cultures to develop a computer model that can be used to predict what approaches or terms are likely to bring two parties together in a successful negotiation. The model is intended to accommodate the i) conceptualization of common and unique properties of culture, at the national, local, and organizational levels of analysis, ii) the influence of context (*e.g.*, prior experience and type of scenario or mission), iii) objective measures of collaboration (*e.g.*, trust, conflict, communication patterns, and self-synchronization), organizational structure (*e.g.*, hierarchical vs. matrixed), and iv) local operational success (*e.g.*, situational understanding, mission success, and second- and third-order effects in an environment).

The validated computer model will lead to recommendations for how to use cultural knowledge to dynamically influence interactions, collaboration, and successful negotiations among team members, friendly, neutral, and especially unfriendly individuals and groups. The cultures of particular interest are the major variants of the

Iraqi, Iranian, Turkish, and other Arabic cultures in that order of precedence. This topic is being managed in close collaboration with ARL-HRED and ARI.

4. Discovering Mechanisms of Bacterial Spore Germination - A new MURI was awarded this year, titled "*Mechanisms of Bacterial Spore Germination and its Heterogeneity.*" The research team is led by Dr. Peter Setlow at the University of Connecticut Heath Center. The investigators aim to determine the mechanisms involved in bacterial spore germination.

Whereas most spores readily and quickly germinate after being exposed to appropriate growth conditions, a small percentage do not. Individual spores may germinate days, weeks, or even months later. The wide time range of potential spore germination clearly has serious implications for medical treatment as well as food preservation. This research topic focuses on the heterogeneity of spore germination with an emphasis on the slow germinating population. The team has developed a facile scheme to isolate and purify pure populations of slow germinating, "super-dormant" spores, a significant advance to achieve their ultimate objectives. A combination of "wet lab" experiments will be combined with computational modeling to dissect the fundamental mechanisms involved. With the understanding gained, the intention is to subvert those mechanisms to stimulate 100% germination "on demand". This topic is being managed in close collaboration with NSERDC.

5. Uncovering Signals Responsible for Mouse and Salamander Limb Regeneration - A new MURI was awarded to a team led by Dr. Ken Muneoka at Tulane University. This MURI, "Signaling Network Interactions Controlling Mouse and Salamander Limb Regeneration" aims to identify and characterize signaling network interactions that control mouse and salamander limb regeneration.

The investigators will establish the molecular genetic foundation necessary for limb regeneration. They will document all transcripts that are modified during salamander limb regeneration. They will then use this data to develop a complete regeneration specific microarray chip that will be used to gather data from mathematical modeling of temporal changes in cellular transcriptomes associated with regeneration, in particular, the reprogramming of fibroblasts. They will model regeneration in the mouse digit tip that is mediated by blastema formation. The modeling is intended to identify specific nodes during the injury response that control whether a wound heals via scar tissue or via reprogramming to form a blastema and eventually regeneration. This information will be used to initiate regenerative therapeutics to be tested on amputated limbs in the rodent model. It is expected that this research will eventually enable capabilities to regenerate lost or damaged limbs or organs in injured warfighters.

B. University Affiliated Research Center (UARC) - Institute for Collaborative Biotechnologies (ICB)

The ICB is operated on behalf of the Army at the University of California at Santa Barbara (UCSB) in partnership with the Massachusetts Institute of Technology (MIT),

the California Institute of Technology (Caltech) and partners in industry. Through its own research and its strategic collaborations and alliances with Army laboratories, Research, Development and Engineering Centers (RDECs), and industrial partners, the ICB provides the Army with a single conduit for developing, assessing and adapting new products and biotechnologies in direct support of the Army mission. In 2009, ARO awarded a renewal contract amounting up to $70M for a five year period to the ICB, consisting of $9.5M in 6.1 funds for FY09. In addition, $4.0M were awarded this year for six 6.2 level projects including two new projects.

The needs of the Army addressed by the ICB include development and improvements in the fields of advanced sensors, materials synthesis, power and energy, information processing, network analysis and neuroscience. Descriptions of the research thrusts and goals for the five ICB 6.1 task orders are described in the following paragraphs.

1. Biomolecular Sensors - The primary aim of this task order is to provide the Army with biosensor platforms of unprecedented sensitivity, reliability, durability, portability, simplicity of operation and integrability. There is a general consensus that a single platform which identifies all possible threats in every conceivable environment by remote sensing and within a living organisms is not likely to be obtained from a single biosensor, or a single set of responsive, adaptive materials. Thus, focus has been given toward the development of complementary and synergistic approaches that will provide the Army with multiple sensing and identification options depending on the target's complexity, source, availability and distance. Device guidelines take advantage of novel hybrid materials, innovative optical and electronic transduction mechanisms, new methods for engineering target-specific proteins, spatially controlling analytes in microfabricated devices and detection paradigms that derive inspiration from nature.

2. Bio-Inspired Materials and Lightweight Portable Energy - The warfighter has a critical need for improved efficiency, portability and safety of energy generation and storage devices and smaller, lighter and more powerful communications, information storage and optical devices. This Task Order seeks to exploit the principles of biological systems that naturally drive nanofabrication, materials synthesis, and energy capture, storage and transduction into the development of useful electronic, optical and magnetic materials and devices and lightweight portable energy and storage systems. This approach is based on the fact that biological materials and assembly pathways offer advantages over traditional processing methods for construction and functional integration of the next generation of microelectronic, optoelectronic and magnetic devices. The application of this approach will involve genetically evolving biomolecular recognition elements to direct the assembly of materials, to dissect the fundamental processes underlying the precision of biological nanofabrication and function, and to translate these mechanisms to radically new methods of synthesis for improvements in electronic, optical and magnetic materials and lightweight portable energy generation and storage.

This past year, a new effort has been launched on the development of biologically-inspired approaches to energy dispersive composites. ICB investigators discovered

previously unanticipated mechanisms by which lightweight biological composites dissipate energy and resist fracture. Some of these mechanisms differ fundamentally from those used in man-made composites. ICB investigators are working cooperatively with those in the Institute for Soldier Nanotechnology (ISN) and with leaders of ARL's WMRD to translate these discoveries into new high-performance, lightweight, energy-dispersive materials.

3. Biotechnological Tools for Discovery - The research thrusts in this Task Order seek to develop new biotechnologies and characterization processes that collectively accelerate the development and characterization of molecular recognition, as well as signal transduction components, molecular self-assembly, catalysts for new energy processes, and multi-functional hybrid materials. This team's efforts are tightly integrated with continuing efforts in sensors, multifunctional materials, and molecular device fabrication. The core tool set for discovery and synthesis in this task order includes: (i) powerful combinatorial methods for synthesis and screening of molecular diversity; (ii) biomimetic and bio-inspired materials for complex functions; and (iii) advanced molecular characterization technologies. Overall, the research conducted in this task order is especially relevant to the Army's needs for biological detection, isolation, identification and neutralization. The continued advancements within this task order provide critical new infrastructure to maintain the ICB's position at the forefront of technology innovation.

4. Bio-Inspired Network Science - This Task Order specifically addresses the Army's long-term need for Network Science and how that plays a crucial role toward the development of a Future Combat System (FCS) that relies on speed, agility and situation awareness rather than heavy armor. Under this paradigm, a multitude of sensors feeds mobile command-and-control centers with real-time data to achieve levels of situational awareness that have no precedent. As an approach toward reaching these long-term goals, the projects in this task order aim at discovering the basic principles that are responsible for the mechanisms by which biological networks are able to operate in a highly efficient manner in challenging environments, with a special emphasis on the principles that can be applied to the design of artificial systems. The discovery of such principles requires a significant research effort in the construction of models for complex biological networks, the development of analysis tools for such networks, and the discovery of structures and architectures for the design and control of such networks.

5. Cognitive Neuroscience - Soldier adaptability and performance is challenged by haphazard conglomerations of military technologies with short life-cycles. This challenge is aggravated by the variability in background, capacity and prior experience that enlisted men and officers bring to the field. Individuals approach warfare problems with distinct percepts, motor skills and individualized cognitive strategies. The research managed within the Cognitive Neuroscience task order uses multimodal brain imaging, genomics, virtual environments and computational modeling to understand the neural basis of individual soldier variability in the execution of operationally relevant cognitive tasks. The long-term, Army-relevant goal is to improve the soldier/technology interface and enhance technology-mediated analysis, decision-making and control. Improvements

would be based on improved simulation and training, more effective information representation and delivery, improved machine/soldier interfaces, and advances in neuroergonomics.

C. Small Business Innovation Research (SBIR) Program - New Starts
The design of the SBIR program differs significantly from many other programs managed by ARO, as described in Chapter 3, *PROGRAM IMPLEMENTATION*.

1. Compounds and Proteins to Improve Cognitive and Physical Capacity through Cellular Energy Production - Two Phase I SBIRs were awarded to identify, design, and test compounds that may enhance cellular energy production.

- *The Energetics of Cognitive Performance: Regulation of Neuronal Adenosine Triphosphate Production,* awarded to Gencia Corporation.
- *Fullerene Nanomedicine to Enhance Neuronal Adenosine Triphosphate Production Capacity,* awarded to Luna Innovations, Inc.

Mitochondria are the powerhouses of the cell and their ability to produce adenosine triphosphate (energy) when needed is directly related to both cognitive and physical performance capabilities in humans. Mitochondrial DNA mutates at a rate ten-fold higher than nuclear DNA. Mitochondrial DNA mutations lead to an increase in leakage of free radicals and a decrease in energetic production capabilities; this is a primary reason why older humans have less energy and are not recruited into the Army. The loss of experienced warfighters to mitochondrial aging has a high cost to the Army. The ability to delay or reverse mitochondrial damage and mitochondrial aging would have a significant impact both on Army recruiting and on soldier physical and cognitive performance capacity. The objective of the proposed research is to identify compounds or proteins that lead to stimulatory effects on mitochondrial adenosine triphosphate production (the key cellular energy source).

2. Development of System for Rapid Analysis of Brain Trauma - A Phase I topic, "*Development of a Fieldable Brain Trauma Analyzer System,*" was awarded to Engineering Acoustics, Inc. for the development of a fieldable minimal traumatic brain injury analyzer system suitable for near front-line use. The investigators aim to use a very innovative approach to assay the interconnections in the brain by exploiting tactile illusions produced by vibrating patterns on the skin. If the person can perceive the illusion, then all is well, and the strength of the tactile illusion is an indicator of health. This system is envisioned to package the needed expertise into an automated low power system that would permit very rapid determination of return to duty decisions, avoiding needless delays for medical evacuation, and thus helping to sustain the fighting force.

3. Rapid Method for Identification of Protein Variants - A Phase I Chemical/Bio Defense (CBD) SBIR, "*Dielectrophoretic Microfluidic Protein Analysis System*" was awarded to Physical Optics Corp. to develop a rapid means of quantifying the relative amounts of protein variants present in a biological sample. Multiple copies of protein coding genes are present in most higher organisms and when they encode enzymes, the

variants usually differ in enzymatic activity. These variations can result in disparate phenotypes depending on the enzyme. For example the variant "make-up" may influence how pharmaceutical drugs are metabolized, or even how tolerant a person is to chemical agents or infection by a pathogen. Research in this area is in its infancy and tools to rapidly and easily identify and determine the relative amounts of protein variants will enable development of personalized medicine for soldier and civilian alike.

4. Hand-held Naphthalene Dosimeter to Monitor Chemical Exposure - A Phase II SBIR, "*Miniature real-time and accumulated deep UV dosimeter for naphthalene exposure*" was awarded to Photon Systems, Inc. This effort focuses on the development of a small reliable hand held naphthalene dosimeter. Battlefield fuels have been transitioned to jet fuel propellant 8 (JP8) for all military operations well beyond the year 2025. DoD is estimated to use 5.5 billion gallons of JP8 each year, and exposure to JP8 represents the single largest source of chemical exposure to DoD personnel. One to three percent of JP8 is naphthalene. Chronic inhalation of naphthalene has been shown to cause cytotoxicity and alveolar/bronchial adenomas in mice. The Environmental Protection Agency is currently reviewing its naphthalene human health risk assessment, and preliminary drafts indicate that naphthalene is likely to be changed from a "possible human carcinogen" to a "likely human carcinogen." Mixtures that contain more than 0.1% of a known carcinogen are classified as carcinogens, thus JP8 may soon be regulated as a "likely human carcinogen." The cost of removing naphthalene from jet fuel is estimated at 27-90 cents per gallon, making the expenditures for removing naphthalene from DoD jet fuel at $1.4–$5.0B per year.

5. High-resolution Protein Separation System - A Phase II SBIR, "*Sequential Isoelectric Point Separation of Proteins Using Non-Gel, Microfluidic System*" was awarded to Lynntech, Inc. The award will fund the development of a high-resolution system that can separate proteins with much greater precision and accuracy than existing 2D gel electrophoreisis systems used for protein separation. The time from sample application to separation is expected to be approximately 15 minutes. Once validated, this system will enable rapid determination of proteomic profiles for a variety of potential applications ranging from medical diagnostics to microbial identification.

D. Small Business Technology Transfer Program (STTR) - New Starts
The design of the STTR program differs significantly from many other programs managed by ARO, as described in Chapter 3, *PROGRAM IMPLEMENTATION*.

1. Controling Bacterial Infections Without Conventional Antibiotics - A Phase I STTR, "*Bacteriophage-Based Probiotic Preparation for Managing Shigella Infections*," was awarded to Intralytix, Inc. to develop a system using bacteriophages in the treatment of specific bacterial infections. This effort is part of a long-standing interest at ARL/ARO to exploit bacteriophage for intelligent control of bacterial infections. Bacteriophages (phages) are a type of virus that are highly effective in killing certain species of bacteria but which do not harm human cells. The investigators will test this approach by isolating and characterizing phages possessing potent activity against a bacterial species responsible for diarrhea, and formulate a phage cocktail with potent

broad spectrum lytic activity against the targeted species. The ability to reduce the incidence of diarrhea would have a significant impact on the readiness and morale of newly deployed troops. In addition, with the widespread prophylactic treatment of farm animals with antibiotics as well as common human use, the emergence of antibiotic resistant bacteria is becoming a significant problem. New approaches are overdue and the use of bacteriophages has significant promise due to their high specificity.

2. Developing New Treatment Strategies for Eliminating Bacteria - Three Phase I STTRs were awarded to develop innovative technologies to effectively treat multi-drug resistant and biofilm-embedded bacterial infections.

- *Innovative Technologies to Effectively Treat Multi-Drug Resistant and/or Biofilm-Embedded Bacteria*, awarded to Caldera Pharmaceuticals, Inc.
- *Novel Antimicrobial Agents Targeting Drug Resistant Bacterial Biofilms*, awarded to Enantigen Therapeutics, Inc.
- *Biometrics for Treating Biofilm-Embedded Infections*, awarded to PolyMedix, Inc.

The widespread use of antibiotics and bacterial adaptation have combined to make antibiotic-resistant pathogens prevalent. To complicate the problem further, bacteria can form biofilms during infection of a host; for example biofilms often develop and persist on medical implants. Once embedded in biofilms, bacteria that are normally sensitive to an antibiotic are protected and will be tolerant to antibiotic concentrations several orders of magnitude higher than normally lethal levels. These awards are aimed at developing effective treatment strategies to eliminate the bacteria, whether they are multi-drug resistant or embedded in biofilms. None of the approaches are expected to produce antibiotics to which resistances could easily develop.

3. Preventing Infections by Modulating Iron Levels - A Phase I STTR, "*Iron Man: Novel Technologies for Autonomous Defense*," was awarded to Caldera Pharmaceuticals, Inc. for the development of a specific iron buffering system to maintain optimal *in vivo* iron concentrations. Iron is critical to all organisms and excessive iron levels are strongly correlated with increased bacterial infections and increased human mortality. The ability to modulate available iron levels when needed has strong potential for preventing prokaryotic infections especially by organisms that are immune or resistant to conventional treatments such as antibiotics, or to supplement conventional therapeutics. The investigators will identify the optimal *in vivo* iron levels for pathogen resistance and develop a buffer with an ability to specifically remove iron from plasma without affecting the concentrations of other metals. Proactive control of iron levels in humans, instead of having the essentially random variability that now exists, has great potential for positively improving both soldier health and performance.

4. Rapid Assay to Identify Compounds that Increase Energy Production - Two Phase II STTRs were awarded to develop a method for identifying compounds that may enhance cellular energy production.

- *Cell-based High Throughput Screening of Compounds Improving Mitochondrial Energetics*, awarded to Agave Biosystems, Inc.
- *Identifying Compounds that Increase Mitochondrial Performance*, awarded to Eon Corp.

These awards fund research to design, construct, and demonstrate proof of concept function for high throughput assays to screen for compounds that increase mitochondrial copy number and/or the efficiency of mitochondrial function. The capabilities of the cellular organelle, mitochondria, are directly relevant to the cognitive and physical performance of the Soldier. The ability to stimulate mitochondrial energy production is expected to extend the time that soldiers remain fit for duty, boost soldier physical and performance capabilities, and expand the age range of suitable recruits.

E. DARPA Surviving Blood Loss (SBL)

Previous ARO-funded efforts on the molecular basis of hibernation have transitioned into a larger DARPA-funded Surviving Blood Loss program. The objective of the Surviving Blood Loss (SBL) Program is to develop novel strategies that delay the onset of irreversible shock and allow an injured warfighter to survive significantly reduced oxygen delivery for extended periods of time. The SBL Program will thus provide increased time for successful evacuation, triage, and initiation of supportive therapies. An interdisciplinary effort is in progress to develop an understanding of the control mechanisms of energy production, metabolism, and oxygen utilization and to identify and control the protective mechanisms that preserve cellular function despite critically depressed oxygen delivery. Specific investigational foci include mechanisms to control the metabolic state on demand, including inducing a state of suspended animation. Animal testing has demonstrated that metabolic activity can be reversibly halted in both mice and pigs, and that entering this state of suspended animation has no effects on cognitive or physical activity, reproduction, or offspring, and that survival after sixty percent blood loss can be increased from twenty to sixty percent. Human testing is expected to begin in FY10.

F. DARPA Revolutionizing Prosthetics Program (RPP)

ARO-LS currently co-manages a large ongoing project funded by DARPA in this research area. The current project is following initial development work of a neurally-controlled arm prosthetic with incorporated sensory feedback. This project works together with a large VA sponsored clinical trial that will culminate in a submission to the FDA approval process for the powered intelligent upper limb prosthetic device. The project has launched and is in the process of producing the advanced prosthetic arms for several VA centers while two additional research laboratory thrusts are pending.

G. DARPA Restorative Injury Repair (RIR) Program

The vision for the Restorative Injury Repair program is to fully restore the function of complex tissue (*e.g.*, muscle, nerves, skin, etc.) after traumatic injury on the battlefield. These injuries include both kinetic (*i.e.*, penetrating wounds) as well as other destructive injuries (chemical and thermal burns, musculoskeletal injuries, blast overpressure, etc.). RIR aims to replace the current concepts of "wound coverage" by fibrosis and scarring with true "wound healing" by regeneration of fully differentiated, functional tissue. The program will achieve its goals by developing a comprehensive understanding of the wound environment, including cellular elements, matrix, inflammatory mediators, growth factors, nutrients, substrate utilization, biofilms, and ultimately processes of morphogenesis leading to anatomic and functional restoration. ARO manages three projects in this program.

H. Defense University Research Instrumentation Program (DURIP)

With provision of FY09 OSD funds for purchase of research equipment used in university efforts relevant to the ARO mission, this program supported research in various areas of interest to ARO-LS. There are eight new projects funded for $1.5M in FY09, including research in prosthetics, human performance, stress resistance, soldier protections, sensors, and bioremediation.

I. Defense Experimental Program to Stimulate Competitive Research (DEPSCoR)

The battlefield deployment of warfighters frequently requires sustained submaximal exercise for multiple consecutive days. Fatigue during these periods of deployment reduces combat effectiveness and exposes the warfighter to increased risk of injury or death due to enemy action, therefore there is a direct benefit to the military of knowledge that can postpone or eliminate the onset of fatigue during sustained submaximal exercise. Dr. Michael Davis at the University of Oklahoma was awarded DEPSCoR funds this year for a project that will use a unique animal model of fatigue-resistance (ultra-endurance racing sled dogs) to investigate the mechanisms of enhanced oxidative substrate uptake as a metabolic strategy to reduce fatigue during sustained exercise. Existing evidence derived from this model suggests that fatigue resistance is associated with the shift from reliance on oxidation of intramuscular macromolecules (glycogen and triglyceride) to transport and oxidation of extramuscular molecules (blood borneglucose and fatty acids). Therefore, experiments are proposed to measure whole body flux of these molecules using sophisticated tracer techniques, with simultaneous measurement of oxidation of fatty acids (the presumed predominant energy source) during exercise. Complementary experiments will be conducted to examine the same phenomenon at a subcellular level using ex-vivo sarcolemmal transport assays performed on muscle biopsies. Finally, the capacity to induce a fatigue-resistant state is presumed to be the product of conditioning-associated changes in gene expression and protein synthesis within the muscle. Therefore, transcriptomic analysis of muscle during training and the induction of fatigue resistance will be performed to identify the relevant pathways and, by inference, the pathways leading to changes in gene expression. This work is expected to provide the

foundation for construction and prospective testing of appropriate training conditions for the induction fatigue resistance in animals and, eventually, humans.

J. Historically Black Colleges and Universities/Minority Institutions (HBCU/MI)

One new research project was initiated in FY09 through this program. Dr. Franklin A. Carrero-Martinez at the University of Puerto Rico was funded to develop biomarkers (antibody-nanoparticle conjugates) to monitor axon growth and to apply magnetic force to alter the paths of axon growth. Monoclonal antibodies to specific axonal extracellular proteins will be functionalized with magnetic nanoparticles. These will be injected into embryonic flies during the synaptic formation period, and visualized through the transparent cuticle. Subsequent physical manipulation of the axons with magnetic fields will test the hypothesis that physical forces can redirect the synapse to arbitrary locations in the target field of muscle. Successful forced migration of the motor axon towards the posterior surface of the muscle will be considered a success in the context of this aim as it could provide a new, non-invasive method in support of neural restoration.

IV. SCIENTIFIC ACCOMPLISHMENTS—Selected Examples

Novel Mechanism of Bacterial Communication Discovered—Caroline Harwood, University of Washington

Bacteria seldom live as pure, single species planktonic cultures in nature. Rather, it is generally accepted that bacteria normally live in consortia composed of multiple species in close proximity to one another and have complex inter-cellular interactions. Most research effort has been devoted to understanding cell-to-cell communications between bacteria of the same or different species. The Harwood laboratory made a ground breaking discovery that indicates there is actually communication between biological kingdoms. The chemical compound (coumarate) used for communication in *Rhodopseudomonas palustris* can only be synthesized if the bacterium is in close proximity to plant material. The bacteria import coumarate which is made by the plant, but not the bacteria. The coumarate is chemically modified by the bacteria and excreted back into the environment, signaling other bacterial cells that a food source is near. Studies are underway to determine if the coumarate derivative or other chemicals are used to communicate in the other direction, *i.e.*, to tell the plant that *R. palustris* is present. Dr. Harwood was recognized this year by being elected a member of the National Academy of Sciences.

Positive Emotional Cues Optimize Attention to Visual Displays—Eran Zaidel, University of California, Los Angeles

A team currently funded by ARO in the Cognitive Neuroscience lab of Dr. Eran Zaidel discovered that brief spatial cues consisting of “happy face” icons can dramatically improve the efficiency of visual information processing. The team used a computerized measure of the attention networks in each cerebral hemisphere (the Lateralized Attention

Network Test or LANT). These networks included prefrontal-anterior cingulate executive attention labeled "Conflict Resolution" (dopaminergic), parietal "Spatial Orienting" (cholinergic), and frontal-parietal "Alerting" or vigilance (noradrenergic). It is important to minimize "Conflict Resolution," *i.e.* minimize the distraction by irrelevant information, and to maximize "Orienting" to a valid spatial cue for maximum performance efficiency. The team found that only cues consisting of happy face cartoons projected to the right hemisphere yielded the desired optimization. By contrast, cartoon cues with angry or neutral expressions reduced attention and impaired performance. Moreover, the optimization was effective only for operators who did not have anxious personalities. The team had already shown that restricting the display to one visual hemifield/hemisphere at a time while responding with the opposite hand mitigates the effects of sleeplessness on the performance of helicopter pilots. The new finding shows that restricting the display to one hemisphere and using happy face icons to focus attention on the targets improves performance in well-rested operators as well. The work may lead to changes in display considerations and alerting methods in crew station design to accommodate the user's emotional subsystems, closing the loop between the Army system and the Soldier. Further work will seek to extend the knowledge of emotional interactions with visual performance in a variety of scenarios.

Keeping Soldiers Alive with Suspended Animation—Mark Roth, University of Washington

Traumatic injury leading to severe hemorrhagic shock remains a significant concern for Army soldiers. Soldiers suffering severe blood loss typically need medical intervention within an hour in order to survive. ARL has funded innovative basic research to develop new interventions for controlling soldier metabolism. Recent research by ARO supported investigator Mark Roth demonstrated that exposure to H_2S gas can block mitochondrial oxidative phosphorylation by binding to and inhibiting cytochrome c oxidase—an enzyme essential for normal cellular respiration (see Figure 1).

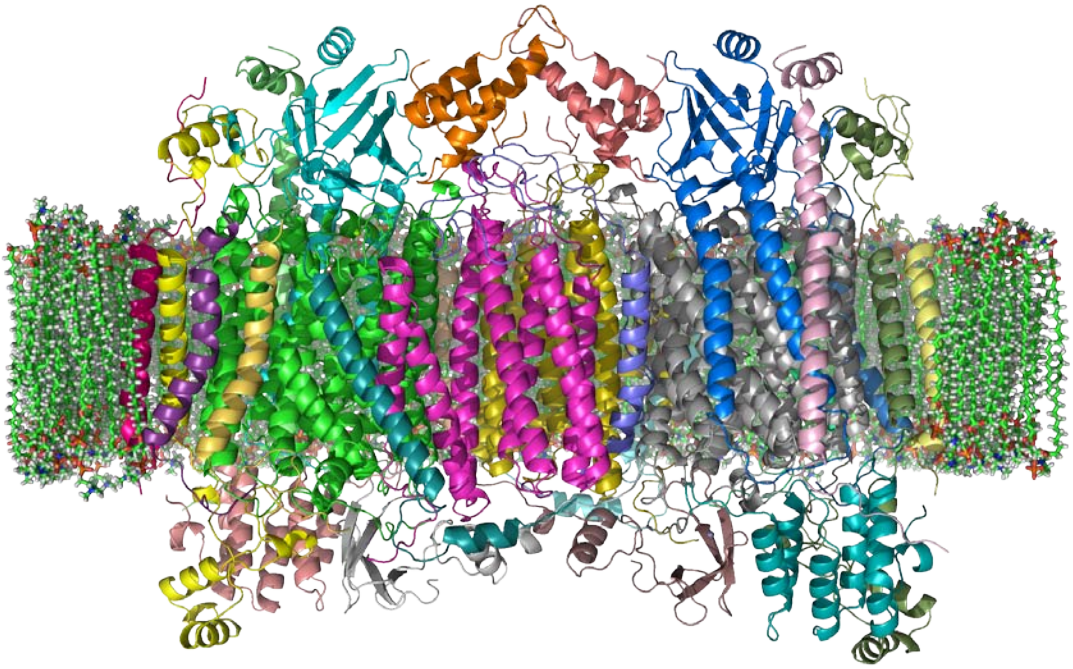

Figure 1. Cytochrome c oxidase, illustrated as a three-dimensional model of the crystal structure. H_2S reduces an organism's metabolic activity by binding and inhibiting the function of this enzyme.

As a result of its ability to inhibit cytochrome c oxidase and mitochondrial oxidative phosphorylation, exposure to H_2S can turn "off" multicellular eukaryotic organisms such as mice, nematodes, and others. In this "off" state, the body temperature drops, the heart stops beating (*i.e.*, metabolic rate decreases), no brain waves are detectable, and the organism exhibits no sign of life (see Figure 2). Interestingly, if H_2S gas is administered at the proper dose, the animal can be brought back to life by simply removing the compound. Furthermore, treated animals exhibit no detectable short- or long-term detrimental effects. While not intended for casual use or intergalactic travel, this technology has obvious implications for casualties suffering severe hemorrhagic shock who would otherwise very rapidly bleed to death. Further research to transition this approach to human therapy is underway. This research also offers the possibility of significant civilian applications, including treatment for trauma and stroke, or any other physiological condition where time is of the essence. Human testing is expected to begin in FY10.

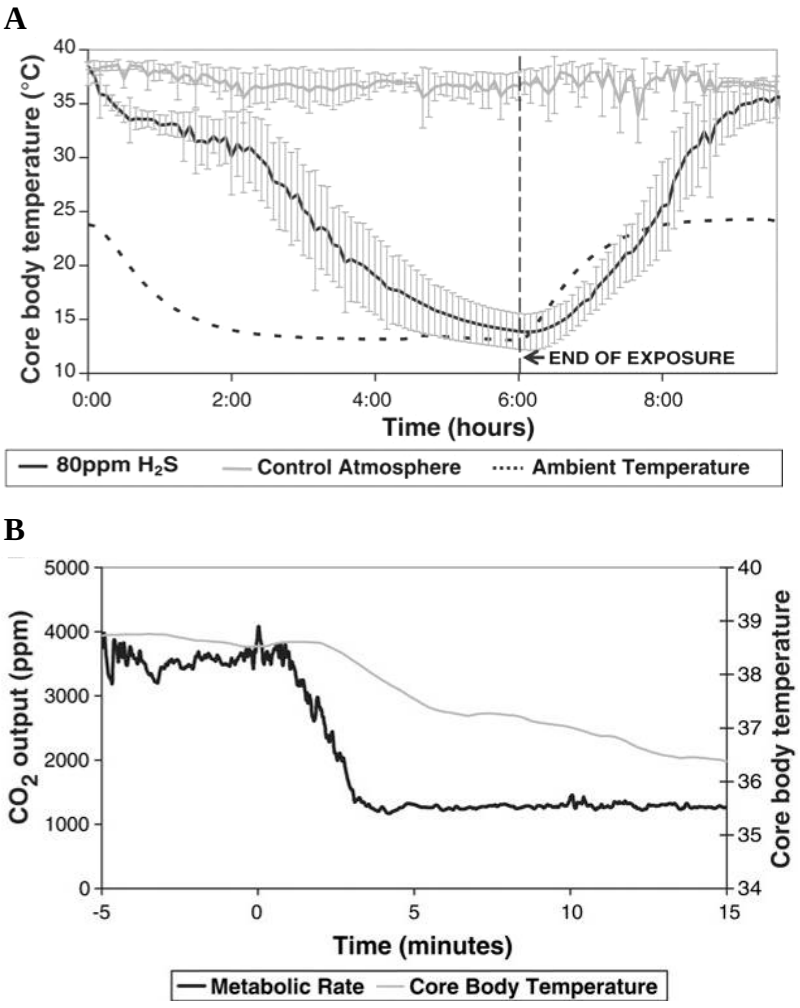

Figure 2. Core body temperature (CBT) and metabolic rate (MR) of mice exposed to H_2S: (**A**) mice exposed to 80 ppm of H_2S (black line) displayed reduced CBT versus mice exposed to otherwise normal air (gray line). The dotted line indicates ambient temperature. (**B**) In addition, the MR of mice (measured via CO_2 output) and CBT decreased significantly after only 5 minutes of H_2S exposure. *[Blackstone et al., 2005]*

Engineering Complex Rotary Motor Proteins for Use in Nanodevices - Mark Richter, University of Kansas

The F1 ATPase motor protein rotates at speeds of up to 700 revolutions per second. This remarkable activity makes the F1 protein an ideal candidate for a molecular motor that could drive microscopic engineering systems. Dr. Mark Richter's research group has been investigating the F1 motor protein with the broad goal of fabricating nanodevices that couple the rotary motion of the F1 motor to useful work on the nanoscale (see Figure 3). Such work could be the ultrasensitive detection of chemical or biological agents or the controlled release of drugs or anti-toxins upon recognition of specific agents in the environment. Dr. Richter's group has successfully engineered a rigid protein arm onto

the central rotating spindle element of the motor (see Figure 3, "protein arm"). The engineered motor protein remains highly active and has been thoroughly characterized biochemically. The introduction of the protein arm is an exciting advance as it will enable attachment of secondary devices (such as a nanoscale electricity generator or a nanoscale pump) at a controlled distance away from the main body of the protein, ensuring that the secondary device can rotate freely without colliding with the motor. Currently the group is investigating methods for attaching secondary devices to the protein arm and for integrating the engineered F1 motor protein onto surfaces at precise locations and in the proper orientation to allow multiple motors to rotate without colliding with each other. Experiments are also underway to engineer a regulatory domain (see Figure 3, "regulator") within the protein to make motor function dependent on the presence of a particular molecule, such as a chemical agent.

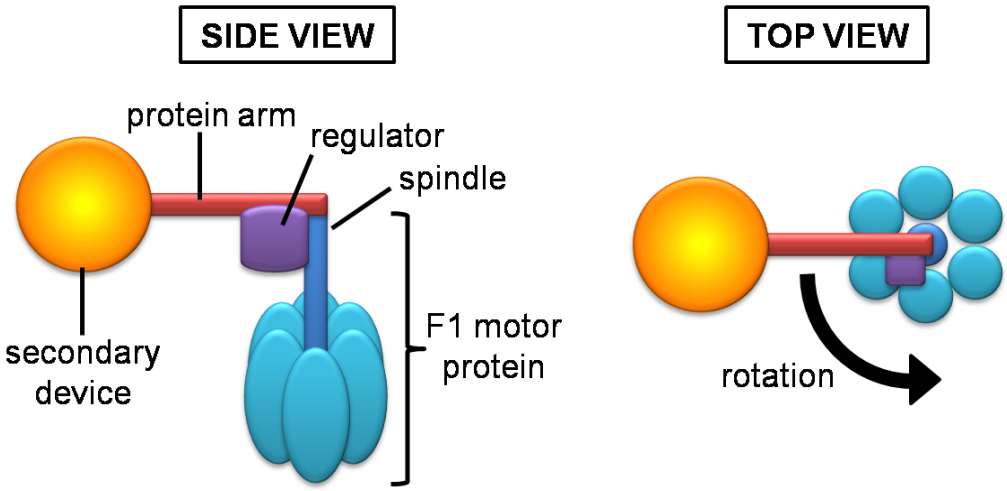

Figure 3. The regulatory domain, or "regulator," within engineered motor protein can produce motor function dependent on the presence of a particular molecule, such as a chemical agent.

Advances in Virally-Templated Flexible Batteries - Angela Belcher, MIT/ICB

Research sponsored by ARL/ARO and conducted at the ICB and MIT has pioneered the use of genetically engineered bacterial viruses to template semiconductors and metals in controlled arrays creating uniquely efficient micro-scale batteries for soldier personal power (see Figure 4). Professor Belcher of MIT, operating within the ICB and working this past year with ARL-SEDD, has focused on qualifying these batteries for Army applications. President Obama featured Professor Belcher's phage-templated high power density battery in a 2009 White House press conference.

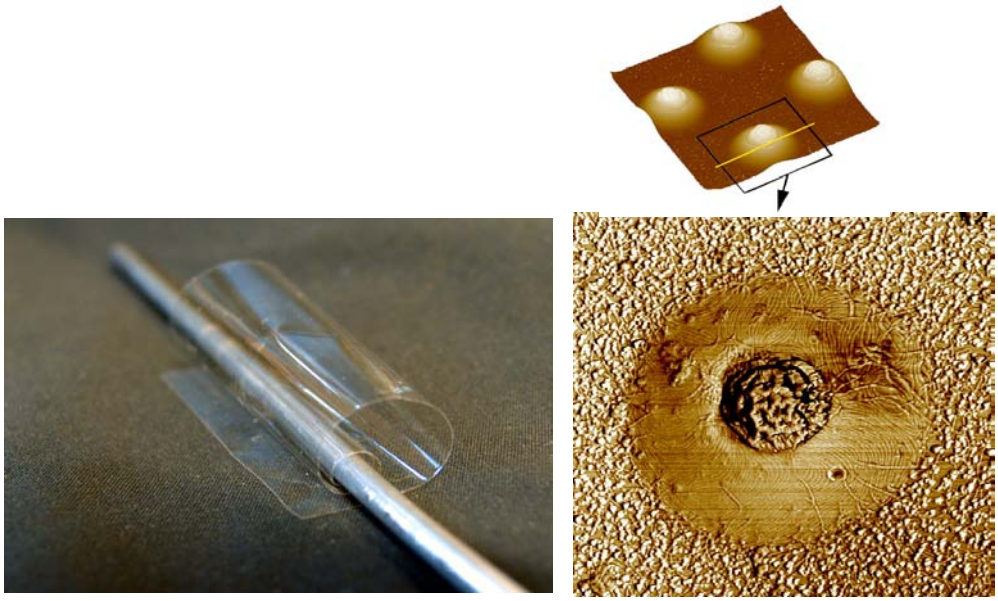

Figure 4. Stamped lightweight flexible batteries: batteries were constructed from genetically-engineered templates. The diameter of the battery shown on the right is 3□m(3 one-thousands of a millimeter).

In this revolutionary route to thin-film conformable batteries, genetically engineered phage were used to synthesize and assemble hybrid nanowires of cobalt oxide and gold at room temperature. Combining this virus-templated synthesis with control of two-dimensional assembly of the viruses on polyelectrolyte multi-layers provides a systematic platform for integrating these nanomaterials to form thin, flexible lithium ion batteries. Performance measurements indicate a specific capacity 3 times higher than that of currently available Li ion rechargeable batteries, with a high cycling rate. The weight of a 10 cm X 10 cm transparent flexible self-assembled cobalt oxide-based battery made by this method is 30 mg. Over the past year, a number of new electrode and electrolyte combinations were explored and optimized. Promising extensions of this technology to fast-switching electrochromic materials, ultracapacitors, RFID devices and catalysts for the production of hydrogen fuel from water also were accomplished over the past year.

V. TECHNOLOGY TRANSFER

Selected examples of research projects managed by ARO-LS that transitioned to the applied research realm in FY09 include the following.

- Four new ICB 6.1 basic research projects moved into 6.2 applied research endeavors involving ARL-SEDD, ARL-CISD and ECBC; others transitioning to industry, DARPA.
- STTR research won a transition contract from the Army Research Laboratory to build, install and support advanced zero-prep EEG monitoring equipment for field evaluation of cognitive state.

- An ARO core funded project transferred advanced bio-sonar data and algorithms to the Corp of Engineers.
- The Biointegrating materials MURI created a project proposal based on their peripheral nerve interface that is currently under consideration by DARPA and MRMC .
- ARO PI funded via STIR in optical imaging of *in-vivo* cortical activity gained NIH funding based preliminary results obtained on the ARO seed money.
- ICB technology transitioned to Natick Soldier Center.
- Co-investment for ICB technology received from COE, ARL-HRED, Dupont, Quallion, IBM, Tamarisc, Coddexis, and Teledyne.
- Funding received from OSD to transition naphthalene dosimeter research.
- Scientific collaboration established between Tetragenetics and Functional Genetics to transition Tetragenetics' protein expression technology to production of anti-viral therapeutics.

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